LOW-RANGE AIRSPEED SENSORS

Ralph E. Duncan

NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

LOW-RANGE AIRSPEED SENSORS

by

Ralph E. Duncan

December 1980

Thesis Advisor: T. Sarpkaya

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The work reported herein is comprised of two parts: A critical assessment of the existing low airspeed sensors for helicopters and V/STOL aircraft and the development of two-dimensional jet-interaction velocity sensors.

The theory of operation, system description, associated electronics, advantages and disadvantages, and the development stage of the existing sensors (pitot-static system, optical convolution velocimeter, low-range orthogonal airspeed system, ultrasonic wind vector

sensor, vortex shedding airspeed system, omnidirectional low range airspeed sensor, swivelling probe air data system, and the fluidic velocity sensor) have been critically discussed.

The need to develop a low-airspeed sensor with no moving parts and a relatively linear sensitivity throughout the operating range and without excessive electronic amplification of the pressure signal led to the exploration of the jet-interaction principle. This culminated in the development of a two-dimensional sensor with extremely encouraging results. Continued design and development will be required to bring the jet-interaction sensor to the point of field tests with helicopters and V/STOL aircraft.

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by

Ralph E. Duncan
Lieutenant, United States Navy
B.S., University of New Mexico, 1974

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requirements for the degree of

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I. AIR DATA MEASUREMENT AND SYSTEM DATA REQUIREMENTS

A. INTRODUCTION AND MEASUREMENT REQUIREMENTS

Air data measurement requirements for helicopters and V/STOL aircraft include omnidirectional low airspeed measurement, wind and gust data at remote and unprepared sites, rapid and accurate determination of sink rate in vertical mode operation, and the measurement of flow angle at low airspeed.

A V/STOL aircraft has vertical takeoff and landing (VTOL) and short takeoff and landing (STOL) capability. The V/STOL flight concept combines direct propulsive thrust with aerodynamic lift for the purpose of extending the conventional flight envelope to include vertical takeoff and landing performance. Both powered lift and aerodynamic lift are needed during the transition maneuver, which is accomplished by vectoring the thrust either by means of a flow-directing nozzle or by tilting the entire aircraft nacelle or rotor.

Present V/STOL aircraft in the U.S. Navy inventory include the AV-8A, UH-IN, HH-2D, SH-2D/2F, HH-3A, RH-3A, SH-3A/3D/3F, VH-3A, CH-46, CH-53A/53D, HH-53B, RH-53A/53D, and VH-53F. Missions include support/reconnaissance, search and rescue, mine countermeasures, and assault transport. Other than helicopters, the only currently deployed V/STOL is the AV-8A Harrier aircraft in use by the marines.

V/STOL flights consist of vertical takeoff, transition from vertical takeoff to conventional flight, transition from conventional flight to hover, hover before landing, and vertical landing. In addition, some flight missions (such as anti-submarine warfare and airborne mine countermeasure) require unique operations such as prolonged low-altitude loiter and hover and prolonged low-altitude, and low-speed sled tow which impose demanding air data requirements. The V/STOL-unique parameters required for these missions include omnidirectional low airspeed, remotely-sensed wind and gust conditions, vertical speed and sink rate, and low speed flow angle information in terms of angle of attack and angle of sideslip. In addition to these V/STOL flight requirements, design limitations and operation environment impose unique demands on the air data system. Lift margin information is needed by the pilot to assure that enough power is available to perform a successful takeoff. Lift margin is the excess potential lift over the weight of the aircraft and is a function of basic air data parameters such as wind velocity, pressure altitude, and ambient air temperature [1].

Unique effects associated with V/STOL operations include ground effect, hot gas ingestion, foreign object damage, power settling, and confined-area quick-turn effects.

For a jet-lift V/STOL, ground effect may either increase or decrease lift, resulting in instability in pitch, roll and heave, and make the aircraft more prone to the influence of

wind and gust conditions. For the helicopter, ground effect normally increases lift. However, damaging ground resonance may occur if certain criteria are not met. Ground resonance occurs due to mechanical abnormalities rather than air data influences, but is so severe in certain helicopters that the rotational energy of the rotor blades induces divergent oscillations of the fuselage on its landing gear. The amount of hot gas ingestion depends on the magnitude and direction of the wind. By orienting the aircraft into the wind, the pilot can minimize its effects. This, in turn, requires wind information. Foreign-object damage is usually caused by the loosening of objects from an unprepared site due to high-speed jet exhaust impingement. Evidently, a knowledge of the magnitude and direction of the wind at the landing site is helpful in reducing the ingestion of foreign objects into the engine inlet. Power settling is caused by the recirculation of the rotor downwash through the helicopter rotor system and results in loss of efficiency. Since excessive sink rates occur during power settling, this can be used as a warning of power settling. The effect of making a quick turn in a confined area results in high sideslip angles, which can cause dangerous roll instability.

Review of accident data has revealed no direct mention of air-data related accidents. However, analysis of the narratives implies that deficiencies in relative wind information and in vertical speed information may be responsible for some of the accidents that are classified as caused by human pilot error.

Among the Navy helicopter accidents, deficient relative wind information and deficient vertical speed information contributed to about the same number of accidents. However, only the relative wind factor caused accidents in the AV-8A V/STOL.

The air data sensors required to generate the combined air data parameters can be extrapolated from the conventional take-off and landing (CTOL) requirements assuming the future V/STOL sensors will consist of CTOL plus some unique V/STOL air data sensors. For future V/STOL applications, these conventional air data sensors will have to meet the more stringent weight, size, power, and cost requirements of the general V/STOL avionics systems. The low-cost requirement becomes especially critical for the helicopter applications.

The V/STOL air data sensors include the omnidirectional low airspeed sensor, the remote wind sensor, the remote gust sensor, the accurate and low-range vertical speed sensor, the accurate and low-range flow angle sensor, and the lift margin sensors. Although there have been a number of developments during the past five years, further improvement is needed. The accuracy of currently available omnidirectional low-airspeed sensing systems is between 2 knots and 5 knots. This magnitude of accuracy seems adequate for most flight control requirements, but is marginal for weapon delivery or remote-site precision hover operations, for which the accuracy requirements are 0.5 to 1 knot. For remote-site precision hovering, the accuracy requirement is the most demanding because of the unavailability

of external guidance and equipment such as that available at a shipboard hovering or landing site.

Most of the currently available omnidirectional low airspeed sensors measure the vector quantity along two axes. Only one of the sensors has the capability to measure the three-dimensional velocity vector. All of the sensors are subject to the influence of the local flow created by the aircraft itself. Installation location is critical in achieving accurate measurements. Almost all of the sensors showed limitations associated with high-speed applications. Some of the sensors present a drag or mechanical integrity problem to the aircraft during high-speed operations. For weapons delivery applications, there is a need to sense the gust component of the relative wind at the aircraft location, and such a capability is not presently available.

Wind gusts severely affect aircraft stability; the accuracy of a weapon being delivered; and the maintenance of the flight path during V/STOL transition, hovering, and landing phases; however, the exact characteristics of the gust that causes these effects are still not clear. Gust information may already exist in the high-frequency portion of the remote wind signal and may simply require a different type of processing. To allow positive identification of the gust indication needed, an in-depth investigation is required. The exact characteristics needed for the various applications can be identified and the method to sense, extract, or process such characteristics established.

Because of the sensitivity of V/STOL's and helicopters to wind shear, it is desirable to determine the wind condition at a remote site before beginning the hovering maneuver. Most currently available remote wind sensors are based on the laser Doppler approach. This techniques utilizes cryogenic cooling and rather heavy equipment. To meet the need of future V/STOL applications, equipment size must be substantially reduced, more extensive test data developed, and other alternatives to the laser Doppler approach examined if it proves to have inherent limitations.

Accurate vertical sink rate is of special significance to V/STOL air data instrumentation because of potential aircraft control problems due to lack of adequate sink rate information. At present, it is recognized that many V/STOL crashes are caused by undetected excessive sink rates. In some cases the lack of response of the vertical speed indication system was at fault. Faster instantaneous vertical speed indicators (IVSI) have been developed, but the results are not yet conclusive. Accidents due to high sink rate still prevail, and it is suspected that the poor accuracy of these devices during vertical mode operations, as well as slow response time, may be a contributing factor.

Accurate angle-of-attack information is required for fire control and weapons delivery. Sideslip angle affects aircraft stability as well as navigation. At low airspeed, the pneumatic flow angle sensors become grossly inaccurate because of

the insufficiency of the impact pressure to yield a reading above the background noise level. At the high speed end, due to the instability of wind-vane devices, large mechanical errors exist. The wind-vane type sensor also exhibits poor performance in the low speed range.

It is evident from the foregoing that the accuracies achievable with the existing devices, using both conventional and V/STOL-unique flight requirements as a basis, are highly dependent on the method of sensing and signal processing. The output parameter accuracy requirements specified will determine the input parameter accuracy needed for a given design appraoch. For example, the omnidirectional low airspeed accuracy requirement for flight control is around ± 5 knots, while the same requirement is 0.5 to 1.0 knots for the fire control applications and ± 3 knots for the navigation applications. Similarly, flow angle measurement accuracy is ± 15 degrees for flight safety, ± 2 degrees for navigation, and ± 0.125 degrees for fire control and weapon delivery.

The results of this study show that at low airspeed and hover, air data sensor technology advances are required. Present omnidirectional low airspeed sensors need considerable improvement in accuracy, directional capability, position error, and environmental capability to survive the high-speed as well as low-speed operations of future helicopters and V/STOL aircraft.

B. SYSTEM DATA REQUIREMENTS

Before one can arrive at a true appreciation of the problem at hand, i.e. assessing all known low-speed air sensors and then developing a system to satisfy given requirements, some understanding of helicopter and V/STOL mission requirements and the unique parameters that are called for is necessary. The concern here is not for the airspeed ranges during which the aircraft is in highspeed forward flight, for there is very little difference between the requirements of the V/STOL and the CTOL aircraft in this range. Rather, the discussion is primarily limited to the airspeed range from zero to 50 knots. It is in this low range that the unique mission segments of the V/STOL arise.

1. Mission Requirements

Perhaps the mission that levies the most stringent demands on the V/STOL aircraft is the anti-submarine warfare action. While operating in this capacity the aircraft is required to cruise to station at a minimum speed of 200 knots, descend to sea level, hover for a minimum time of one hour, and then return. It is during the hover time that the V/STOL is performing the task uniquely its own. During extremely low altitude hover the pilot must accurately know his altitude, vertical sink rate, and his lateral velocities. To date, radar altimeters have served satisfactorily. However, with the existing airspeed sensors, the pilot essentially does not know his airspeed (vertical and lateral) closer than ± 5 knots.

At hover velocities (less than 5 knots) this is unacceptable. Typically, the pilot gauges his lateral drift by the tether angle of his sonar buoy. In addition, the environmental strains on every part of the aircraft are tremendous during this operation with sea spray literally engulfing the aircraft.

Another mission where heavy demands are placed on the aircraft is that of minesweeping. In addition to requirements similar to the ASW mission, two helicopters may in the future be required to exchange tow cables while in flight. This requires precise omnidirectional airspeed and altitude information.

Other mission areas that place similar but probably not as severe demands on the V/STOL include external cargo lifting and marine assault transport.

2. Mission Segments and Required Parameters Unique to V/STOL Aircraft

The V/STOL aircraft is only able to complete missions such as those discussed above because of its ability to perform certain maneuvers that are beyond the capabilities of fixed wing aircraft. Maneuvers such as vertical takeoff, shipboard vertical landing and hovering, transition from vertical to lateral flight, and remote site hovering and landing allow V/STOL aircraft to perform functions, and require that certain unique parameters be monitored. These parameters include omnidirectional airspeed, remotely sensed wind and gust conditions, vertical speed or sink rate, angle of attack, and angle of sideslip.

3. V/STOL Operational Limitations

Limitations associated with V/STOL flight stem primarily from limited directional control during approach, transition, and hover and external wind effects. Of major concern in this discussion are the limitations that arise out of wind effects whether in flight or on the ground.

On the ground, prior to rotor engagement, airspeed information is often as critical as when the aircraft is in flight. With improper wind conditions a rotor engagement by the pilot could cause serious damage due to excess flapping of the rotor blades. Figure 1 shows the wind limitations for starting and stopping rotors. Figure 2 illustrates the relative wind limits for launch and recovery of one type of helicopter. Similar limitations are placed on other aircraft. Thus, the importance of knowing the airspeed as accurately as possible during the pre-launch and launch phases cannot be over-emphasized.

Once the aircraft is in flight the importance of precise airspeed information varies, decreasing sharply at airspeeds greater than about 40 knots. As the aircraft approaches zero airspeed the maneuver margin becomes extremely important. As airspeed drops, the power required for level flight rises dramatically to nearly 90 percent of the total power available. The maneuver margin (the difference between the power available and the power required) decreases. Figures 3 and 4 illustrate the concept of maneuver margin. It is clear that precise knowledge of airspeeds in the low maneuver-margin region can be extremely beneficial.

Nearly every other operational limitation becomes more severe and critical at lower airspeeds. Roll stability is much more difficult for the pilot to evaluate because of the subtleness of the force cues available. Accurate data on magnitude of airspeed, angle of attack, and sideslip angle would be advantageous. Tail rotor vibrations, known as "tail rotor buzz", may occur. It is possible that these could be anticipated with accurate airspeed information. Tables I and II reveal several types of accidents that may be directly or indirectly related to inadequate air data information [1].

4. <u>Summary of Air Data-Related Deficiencies</u>

(a) Lack of adequate omnidirectional sensing systems;

(b) Lack of instruments capable of sensing gust and wind conditions remote from the aircraft;

(c) Lack of vertical airspeed sensing instruments with adequate accuracy and dynamic response;

(d) Lack of accurate flow-angle measurement instruments capable of operating in the low-speed regime;

(e) Lack of a helicopter lift-margin determination system. This would not be required for air data system computation, but only for pilot display to allow real-time assessment of hovering capability.

5. <u>Air Data Sensor Requirements</u>

An extensive survey of the opinions of the individuals in the V/STOL and air data systems industry has been conducted to determine the future requirements for air data sensors.

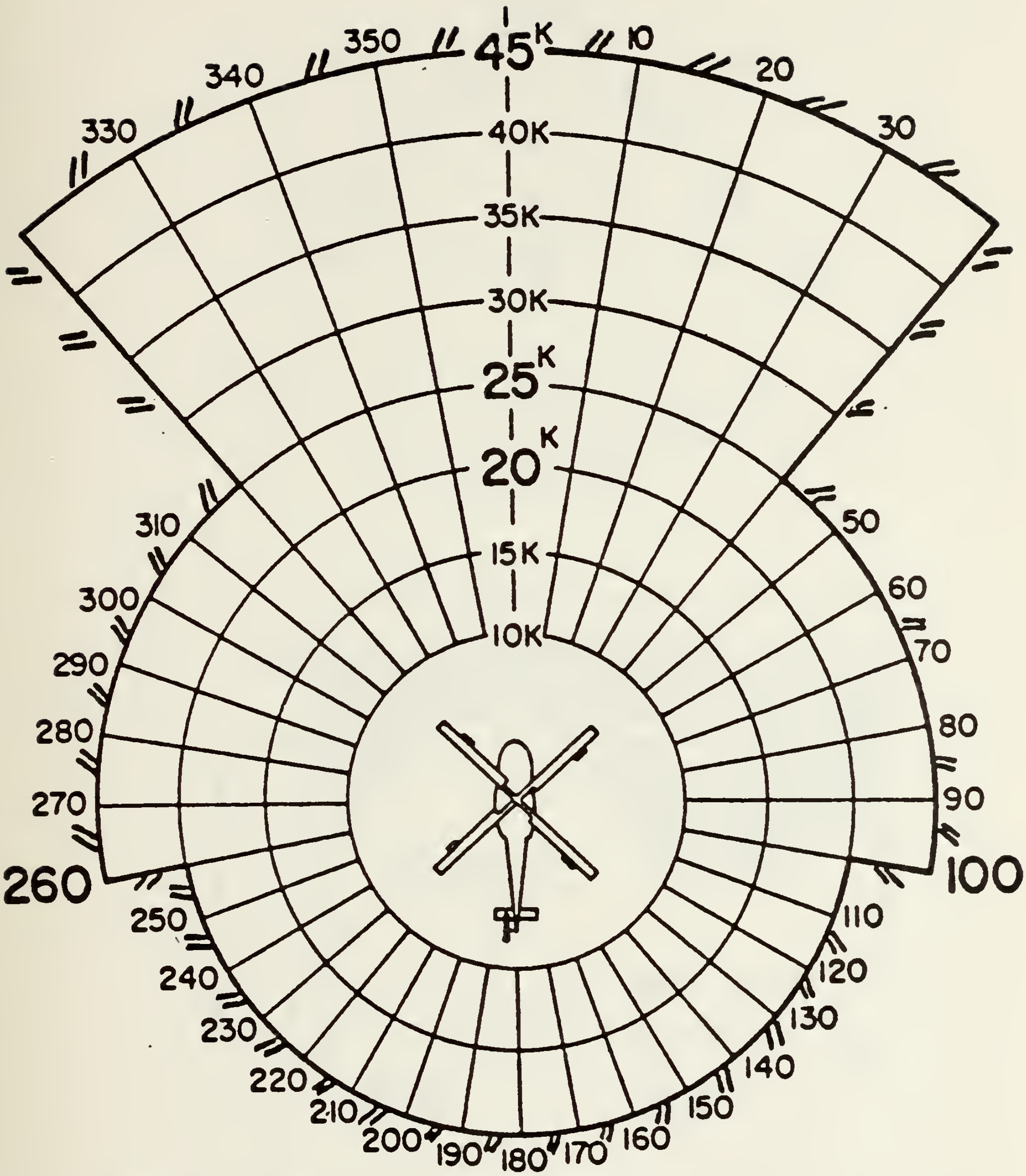


Fig. 1 Maximum wind for starting or stopping rotors. This a typical diagram prepared for pilot reference for rotor engagement and rotor disengagement

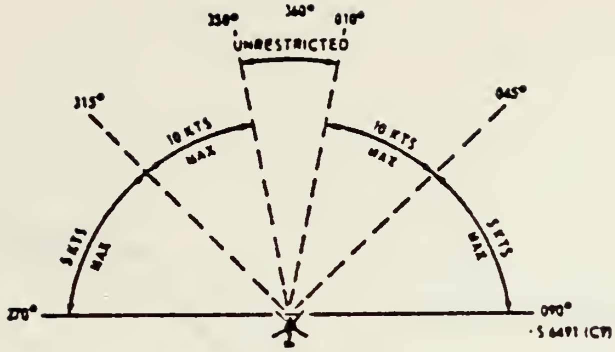


Fig. 2 Wind limitation profile
for launch and recovery,
H-3 helicopter.

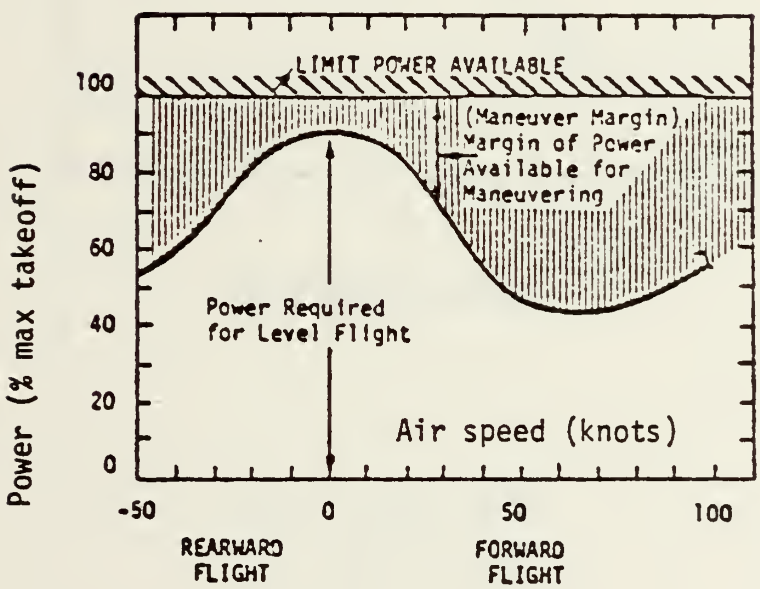


Fig. 3 Power requirement in
level flight

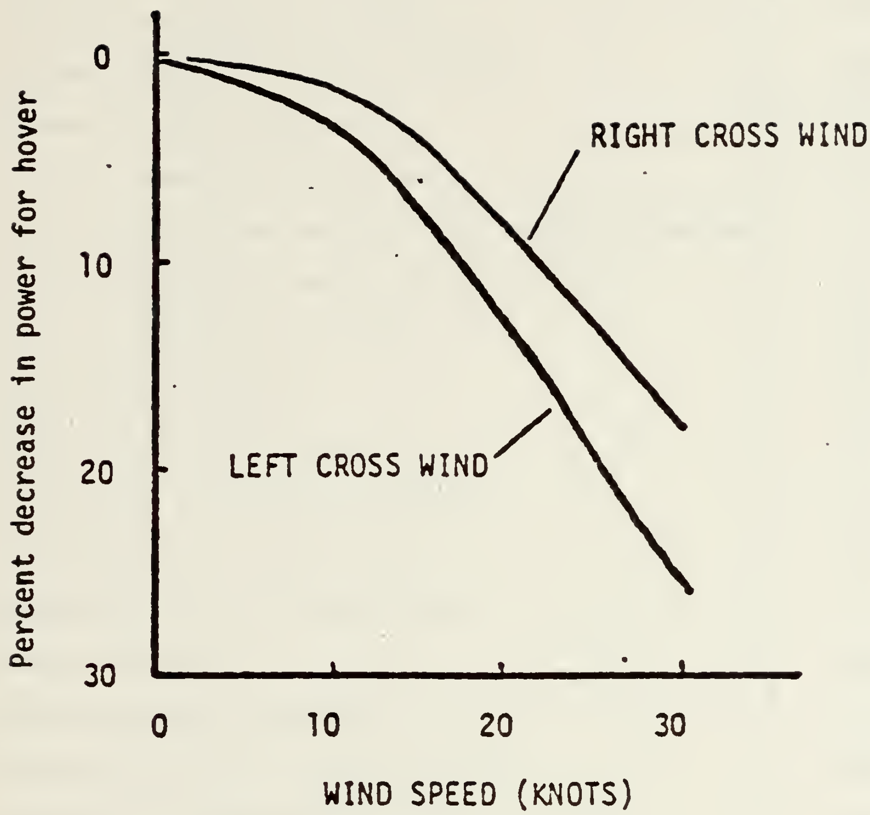


Fig. 4 Power requirement as a function of crosswind component

Table I

Types of Accidents

PILOT ERROR FACTORS

Causal Factors	Percentage
1. Miscellaneous errors	19.2
2. Misjudged distance, altitude, or position	11.8
3. Failed to see aircraft or object	9.92
4. Improper use of flight control in air	9.87
5. Inadequate flight preparation	9.45
6. Failed to supervise flight properly	7.41
7. Violation of existing regulation and NATOPS instructions	4.71
8. Faulty performance of other pilot in aircraft	4.08
9. Failed to maintain flying speed	3.93
10. Misused engine controls	3.58
11. Failed to compensate for wind	2.07
12. Physical/mental condition of pilot	2.07
13. Misused controls on the ground	2.02
14. Exceeded ability and/or experience	1.74
15. Improper level off	1.66
16. Failed to extend landing gear	1.54
17. Improper use, miscellaneous equipment	0.907
18. Improper instrument procedure	0.856
19. Improper use and/or inattention to fuel system	0.856
20. Waveoff	0.756
21. Selected unsuitable terrain	0.554
22. Improper response or poor technique for CV/LPH landings	0.554
23. Exceeded stress limit	0.327
24. Became lost	0.0756
25. Retracted landing gear	0.0252

Table II

SUMMARY OF CH-46 ROTOR STRIKE ACCIDENTS

Causes	Occurrences	Percentage*
1. Wind or weather conditions	21	43
2. Uncertain, but suspected wind or weather effects	9	18.5
3. Mechanical failure	10	20.5
4. Pilot error	1	2
5. Other personnel errors	8	16

*Total number of rotor strike accidents = 49.

The following discussion presents what seems to be generally agreed upon requirements for airspeed sensors of the future [1].

a. Performance Requirements

(1) Remote wind and gust sensors should be airborne vice ship borne;

(2) For flight safety, airspeed should be obtainable to ± 3 knots and ± 15 degrees;

(3) For navigation and instrument flying, airspeed should be obtainable to ± 3 knots and ± 5 degrees;

(4) For fire control, angle of attack should be obtainable to 0.5 degrees, ± 0.25 degrees. Sideslip angle should be obtainable to 1.0 degree (no error is given, however, it should be similar to that for the angle of attack);

(5) Transition velocity should be obtainable with a 5 percent accuracy; and

(6) Sensor dynamic response based on human factor inputs should be greater than 1 Hz.

In addition to the above requirements, the input sensor must be omnidirectional, lightweight and not greatly influenced by external flow variations such as downwash and vortex shedding on the main rotor.

b. System Design Requirements

Matters of critical importance concern hardware, software, data transmission, reliability and maintainability, life cycle costs, and standardization of equipment.

(1) Hardware: One of the most demanding constraints in the design of an air data system is that of weight. In the existing systems as much as 75 percent of the weight is taken up in the packaging and mounting of components. Substantial weight reduction will require liberal application of the high technology electronics to reduce the physical size of the system.

(2) Software: Computations are expected to remain simple with computer requirements similar to CTOL air data systems (ADS).

(3) Data transmission: Closely related to hardware and reliability requirements, there will be a need for rapid data transmission (possibly with fiber optics) and sufficient redundance to prevent catastrophic failures.

(4) Reliability and Maintainability: Because of the severe consequences of system failure in the vertical flight mode and a "safe-return-to-base" philosophy, there must be efficient and sufficient redundancy without excess hardware. This presents an important optimization problem to the design engineer. Additionally, as a direct result of operating with smaller ships (without adequate test equipment), the V/STOL ADS should possess a sufficient number of its own testing functions to aid in maintenance.

(5) Life cycle costs and standardization: In the past, ADS equipment has been procured on a custom-design basis. While this method allows extensive tailoring and flexibility in the airframe design, it proliferates high ADS costs and non-standard support. Increased costs show up not only in short term initial procurement but also in long term areas such as training and maintenance. If equipment standardization is pursued many of these costs can be reduced. Successful standardization has, however, its own set of requirements. There must be provisions for technological-development support, tailoring of the system to special applications, and designer innovation to preclude obsolescence.

C. A CRITICAL ASSESSMENT OF LOW AIRSPEED SENSORS

1. Pitot Tube

Before attempting a full discussion of the newly developed airspeed sensors, it is important to delineate the specific problems associated with the Pitot tube which has served as the old standby for a long time.

First, the Pitot tube is unidirectional. In general, the impact tube is mounted rigidly to the nose of the aircraft and the static tube is mounted on one or both sides of the aircraft. Both pressures are piped to two remote pressure transducers (an expandable bellows in its simplest form, see Fig. 5).

This system measures only the component of relative wind that is parallel to the aircraft attitude line, with many undeterminable effects produced by the cross-wind and gust velocity and varying angle of attack. An additional drawback of this set up is that the static port could be under the influence of an adverse pressure variation. The directional dependency of the pitot tube is also coupled with a sensitivity to the aerodynamic shape of the sensor. It is only during the past few years that meaningful experiments have been carried out in the area of aerodynamically-compensated probes [7].

The use of a remote transducer and associated piping introduces an entirely different set of problems such as water accumulation, pneumatic lag, maintenance problems (often more than 50 pipe joints requiring up to 4 hours per flight to retighten), and shock and vibration damage. The old practice of using metal piping was discontinued in favor of plastic pipe. However, while the pipe-joint problem was solved there still remained the old problems of water accumulation and time lag. The use of plastic pipe gave rise to a new problem: the flexible tube often stretched out of shape and wore on metal framing.

The compressibility of the fluid becomes an important factor on the accuracy of measurements as the volume of the transmission lines and the sensor is increased and is the frequency of flow vibrations increases.

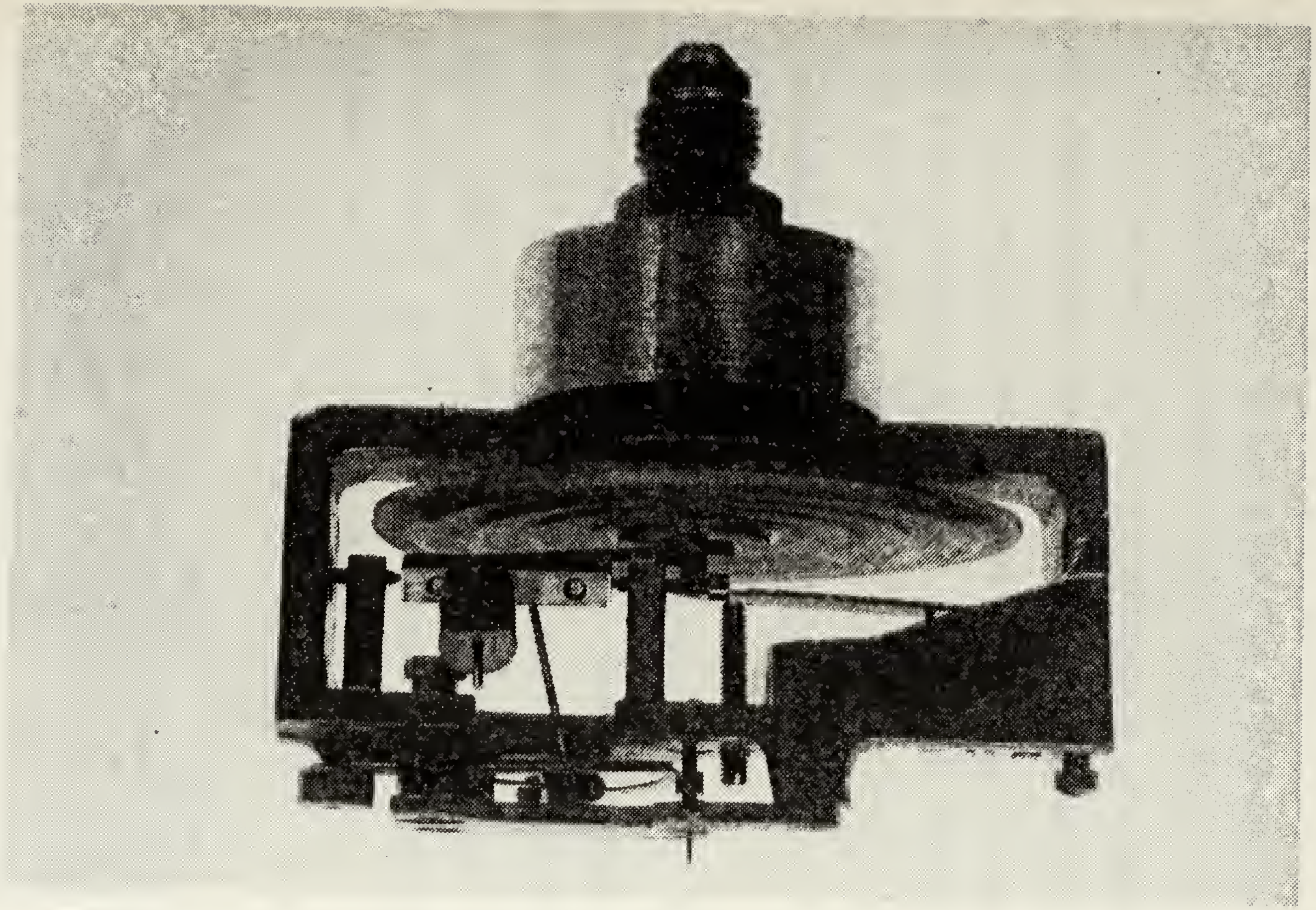


Fig. 5 Mechanical bellows transducer used on older pitot tube systems

One additional factor that must be considered when searching for a new type sensor is the inherent sensitivity of the sensor itself. In a Pitot-static tube the velocity is determined as a result of the pressure differential sensed. Since the differential pressure is proportional to the velocity squared, very low velocities are difficult to measure with any accuracy. Thus, one is left with the fundamental question "is the V^2-relation the determining factor when choosing or designing a new sensor and can the errors be reduced sufficiently or corrected out?"

2. Optical Convolution Velocimeter

a. Theory of Operations

This instrument is developed by Bolt, Beranek, and Newman, Inc. of Cambridge, Mass [2]. The principal of its operation is that flow in the airstream is visualized by a shadow-graph optical system and the speed at which the shadows cross a grating is measured as a frequency. The layout of the instrument is shown in Fig. 6.

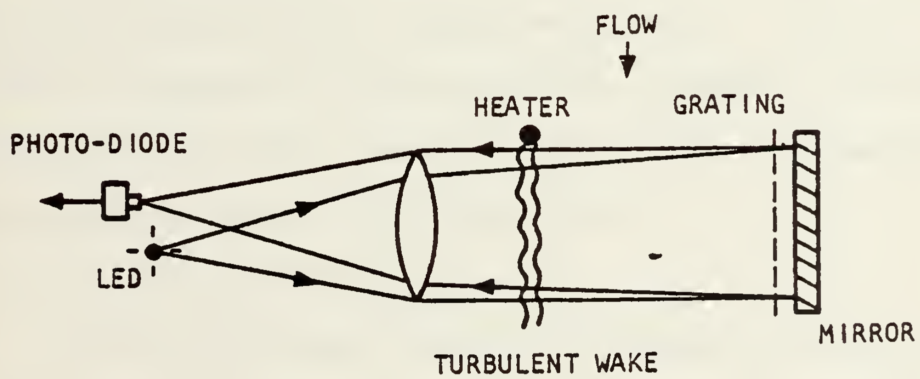


Fig. 6 The Optical Convolution Velocimeter [2]

b. System Description

The shadowgraph optical system consists of an infrared-emitting diode source whose output is collimated by a lens. This parallel radiation is projected through some density variations which have been artificially introduced into the flow. In low subsonic flow, these variations are induced by a heater upstream of the measuring region. In supersonic flow, the wake of a sharp body would be suitable. These density variations cause the radiation to be refracted and focussed or defocussed on the far side of the flow where the radiation falls on a reflective grating. The light that strikes the grating and is reflected back to the photo-diode varies in intensity according to the light and dark patches on the grating. By knowing the period of the grating and measuring the frequency of the reflected light, one can determine the average flow velocity.

A prototype OCV was constructed as shown in Fig. 7. The cyclindrical housing is of brass and contains the light emitting diode, photo-diode, and preamplifier. The f/4 collimating lense is mounted on one end of the housing. The grating (12.5 line pairs per inch) and mirror assembly are mounted away from the housing by four 2 1/2 inch posts.

c. Associated Electronics

The sensor head requires a preamplifier in order to boost the output signal so that it can be transmitted along moderately long cables without fear of interference. The

preamplifier circuit is shown in Fig. 8. At the output of the preamplifier the signal frequency must be measured. There are three potential methods for accomplishing this task: frequency counter, phase-locked loop, and frequency-locked loop. The frequency counter is of any suitable make that can be purchased on the open market. The block diagrams for the phase-locked loop and the frequency-locked loop are shown in Figs. 9 and 10, respectively.

The phase-locked loops, which are commonly used in communication instruments, are built in single integrated circuits. The feedback loop brings the voltage-controlled oscillator to the same frequency as the input signal, and a counter measures the frequency of this oscillator. The phase-locked loop has the advantage of a narrower bandwidth, which is determined by the low-pass filter. Hence, this device has less noise, and weaker signals can be detected.

The frequency-locked loop is similar to the phase-locked loop except that it has a frequency-to-voltage converter instead of a phase detector. The frequency-to-voltage converter enables the device to lock onto a signal without manual tuning. Unlike the phase-locked loop, this device does not have the problem of harmonics.

d. Advantages and Disadvantages of OCV

There are two advantages to the OCV. The first, and probably the most important, is that there are no moving parts. This, more often than not, implies less maintenance

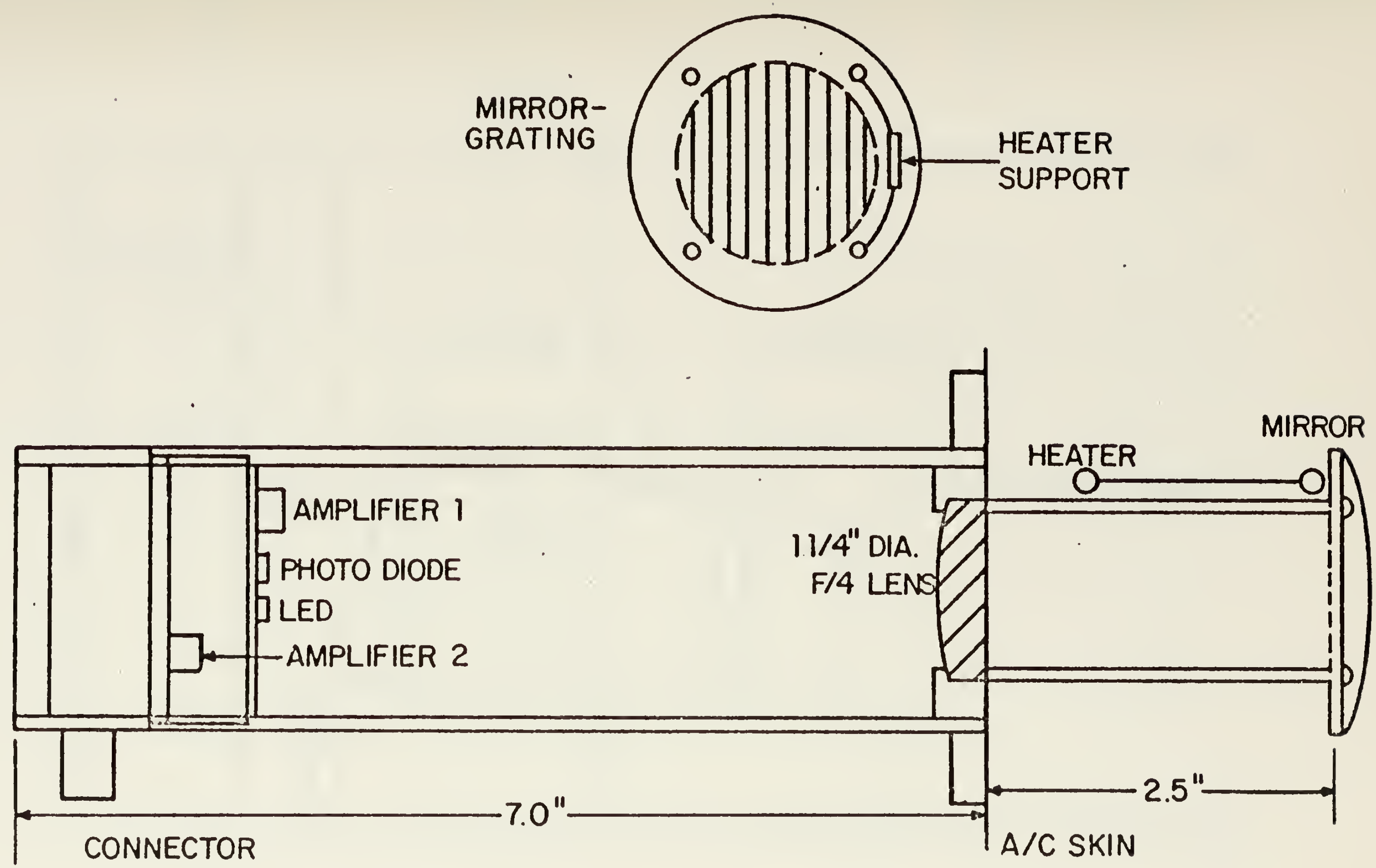


Fig. 7 OCV Sensor Head, Mirror Grating and Heater Support [2].

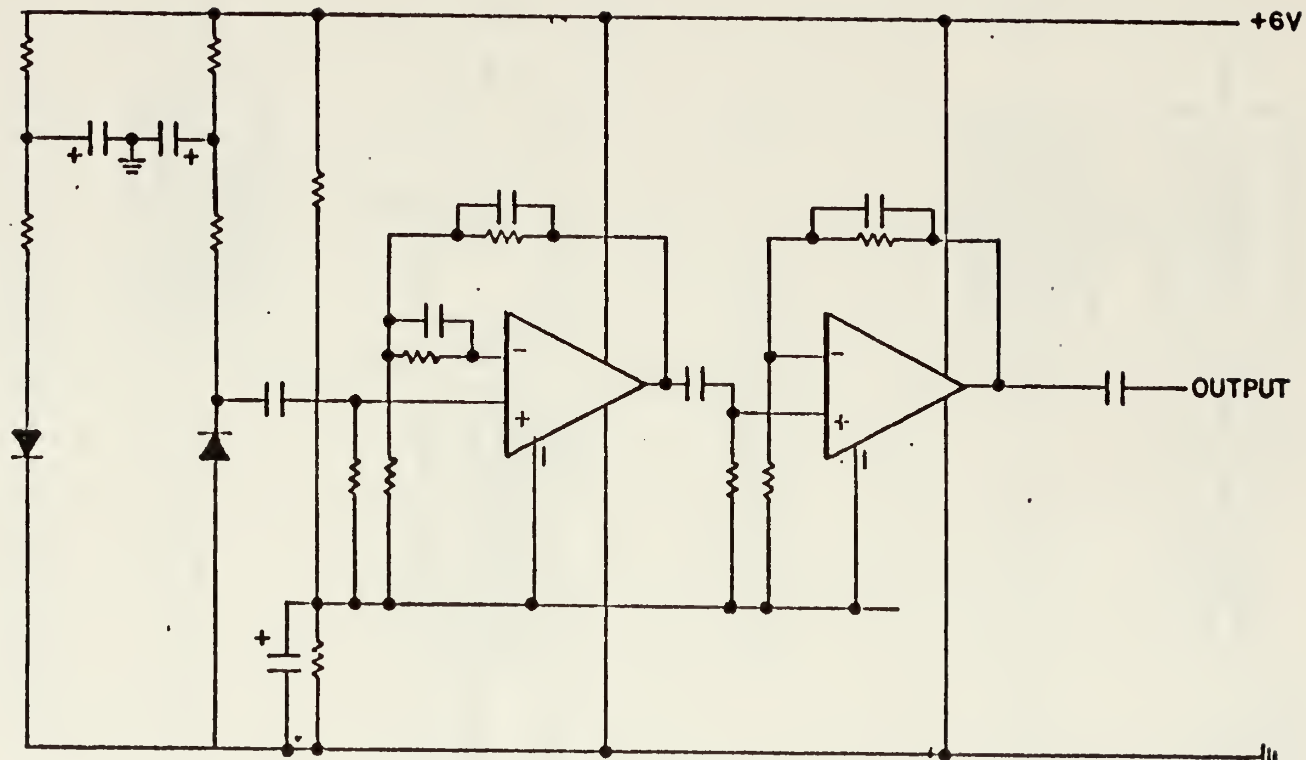


Fig. 8 OCV Pre-amplifier Electronic Circuit [2].

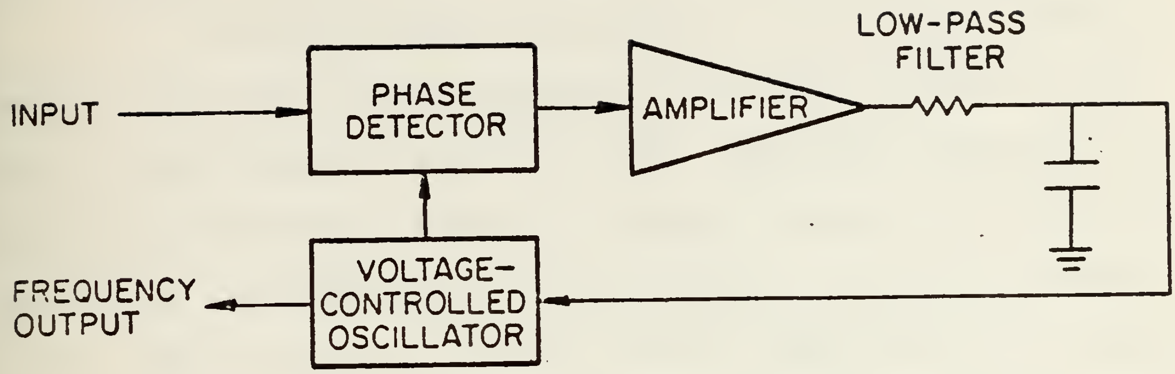


Fig. 9 Phase-Locked Loop [2]

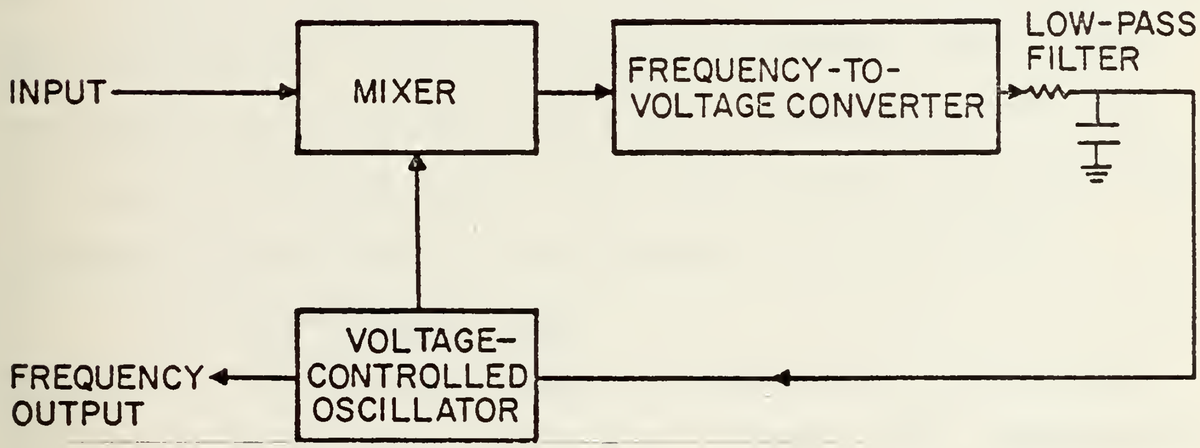


Fig. 10 Frequency-Locked Loop [2]

than those sensors with moving parts. The second possible advantage is that the OCV appears less susceptible to icing than standard Pitot tube because of its large opening.

Unfortunately, the possible disadvantages seem to heavily out weight the advantages. The most obvious at this point is the lack of omnidirectional capability which will be absolutely necessary in future airspeed sensors. Second, the developers estimate that OCV can achieve accuracies around ± 5 knots. While this is certainly better than that of the standard Pitot tube, it is not sufficient to meet the fire control and navigation requirements levied. Third, the OCV, at least in its present stage of development, would appear to be highly susceptible to vibration and shock. This area will have to be investigated further during the actual flight tests. Fourth, the OCV is also susceptible to adverse effects from rain, dust etc. settling on the mirror. Finally, serious errors can be introduced by variations in the flow through the OCV. The flow can be affected by pitch and yaw and the flow-field distortion such as occurs in the downwash of a helicopter.

e. Development Stage

In the early stages of development a prototype model was tested under the wing of a Cessna 172. Results were significant enough to warrant further investigation. Figure 11 compares velocities as measured by the OCV to those obtained by the Pitot tube of the aircraft. As of 1978 further tests have been conducted in an environmental wind tunnel. While

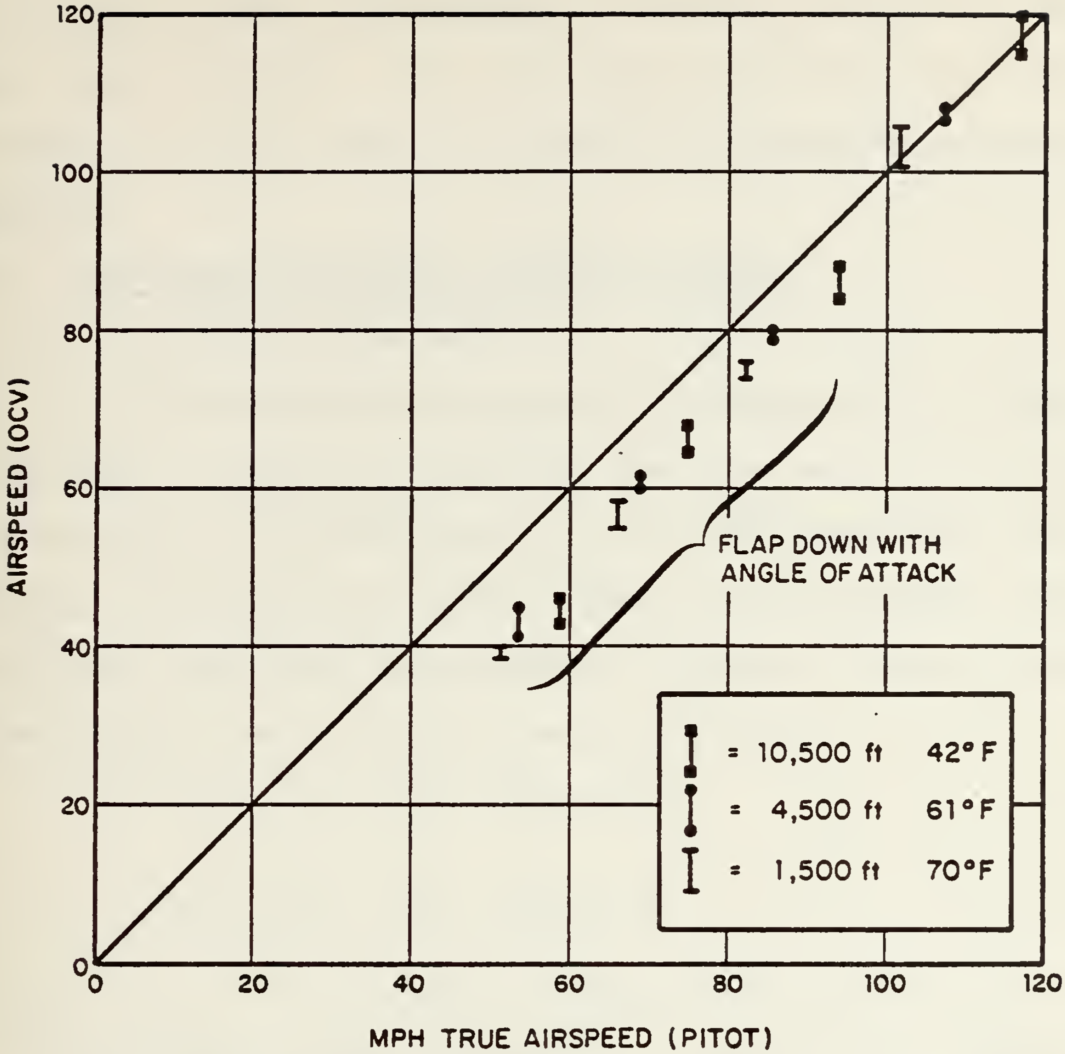


Fig. 11 Comparison of OCV and Aircraft Airspeed Indicator [2]

the developer claims "satisfactory" results, no specific test results were disclosed. The next phase of testing which had not begun as of this report is the field testing under actual conditions.

3. Low-Range Orthogonal Airspeed System

a. Theory of Operation

This system, developed by Rosemount, Inc., Minneapolis, Minn., utilizes a pressure type flow sensor where the pressure output is proportional to the flow angle and impact pressure. Sensing parts on the sensor are located (see Figs. 12a and 12b) such that the pressure difference between opposing chambers obeys the following relations [3,4]:

$$\Delta p_x = (p_1 - p_2) = Aq_c \cos^2\theta \qquad (1a)$$

$$\Delta p_y = (p_4 - p_3) = Aq_c \sin^2\theta \qquad (1b)$$

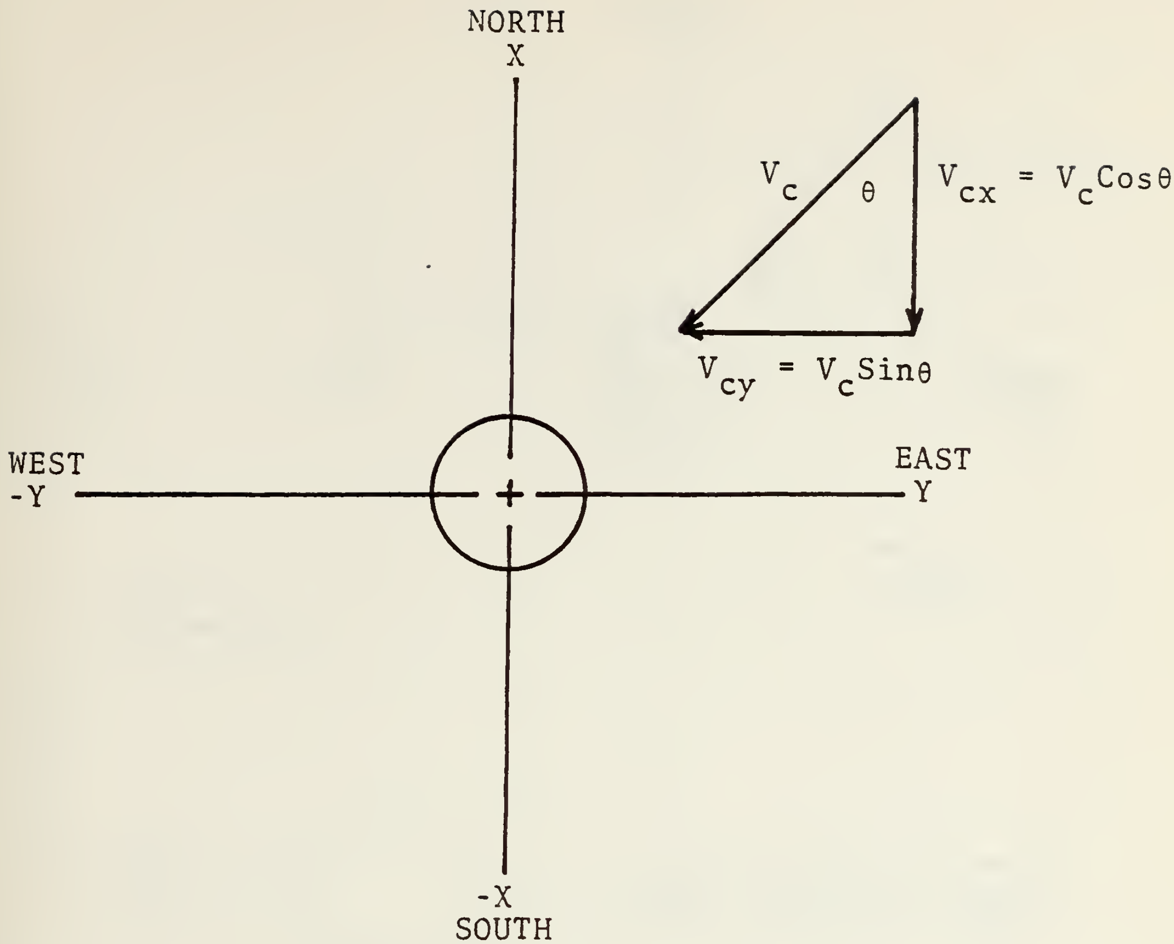
where $q_c = 0.5\ \rho V^2$ (the impact pressure); p_1, p_2, p_3, and p_4 are the pressures in the chambers 1 - 4; and A is a calibration constant. Noting that $V\cos\ = V_x$ and $V\sin\theta = V_y$, the final equations for the calibrated velocities become:

$$V_{cx} = K(\Delta p_x)^{1/2} \qquad (2a)$$

$$V_{cy} = K(\Delta p_y)^{1/2} \qquad (2b)$$

$$V_c = K(\Delta p_x + \Delta p_y)^{1/2} \qquad (2c)$$

Where K is the final calibration constant including A and ρ. The voltage output can be made proportional to the airspeed.



V_{cx} = Calibrated North-South Orthogonal Wind Speed

V_{cy} = Calibrated East-West Orthogonal Wind Speed

V_c = $[(V_{cx})^2 + (V_{cy})^2]^{1/2}$ = Calibrated Wind Speed

θ = Arctan (V_{cy}/V_{cx}) = Wind Direction

Fig. 12a Notations for Orthogonal Wind Speeds V_{cx} and V_{cy} [3-4]

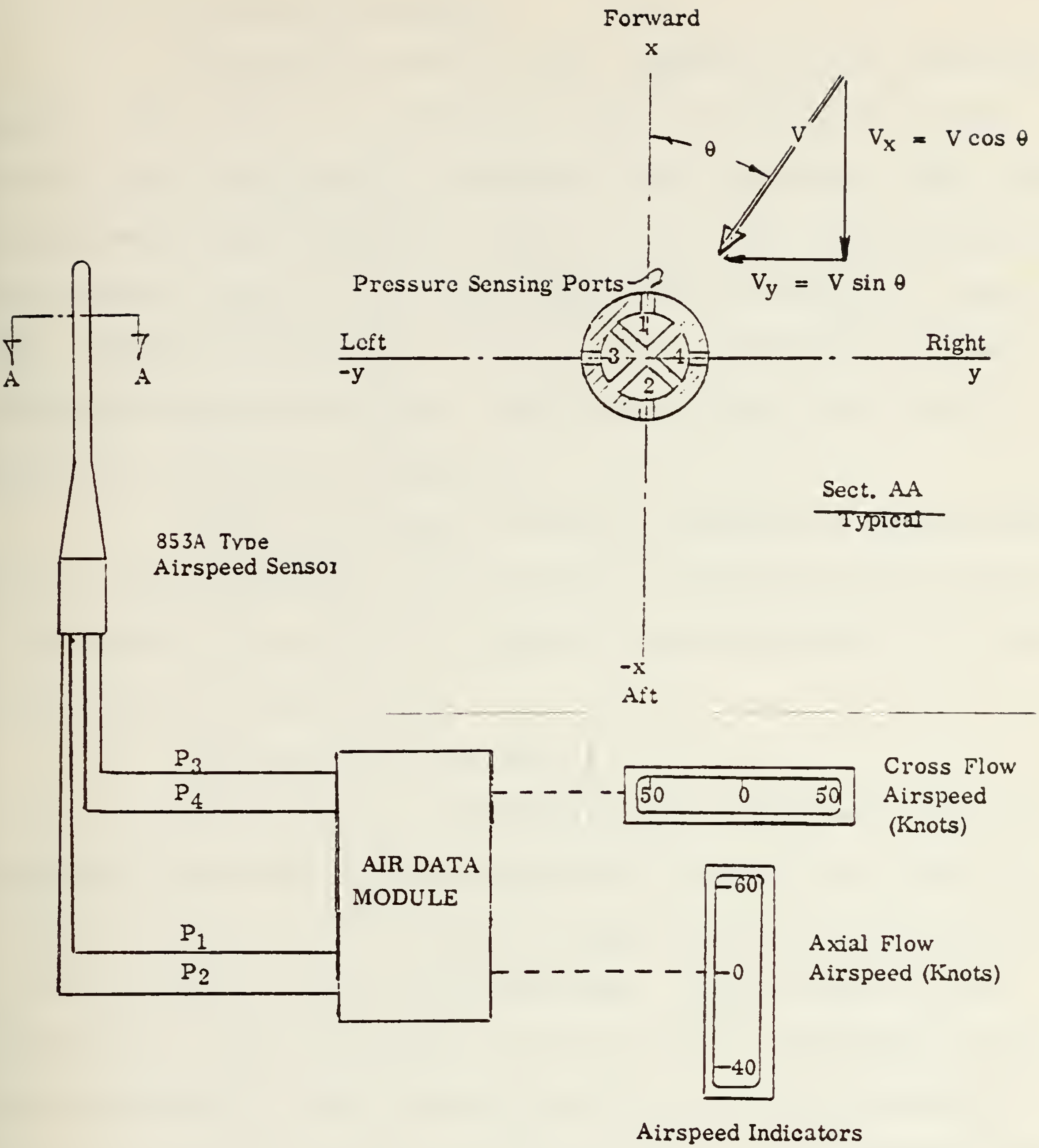


Fig. 12b Schematic Drawing of Typical Orthogonal Airspeed System [3-4]

b. System Description

Figures 13a and 13b show drawings of the Rosemount sensor. The sensor is cylindrical with a hemispherical head. In the body of the sensor are drilled four chambers. The sensor is mounted so that chambers 1 and 2 are in the fore-aft direction and chambers 3 and 4 are in the athwartship direction. These four chambers provide the pressure signals required to obtain the outputs described above. Additional static ports may be added for altitude measurements.

Sensor in-flight de-icing is generally accomplished with a self-regulating resistive heater providing heat from 150 to 275 watts. The sensor is generally mounted above the rotor for helicopter applications.

c. Associated Electronics

Because of its simplicity and proclaimed accuracy, Rosemount sponsored the development of a capacitive transducer. As shown in Fig. 14, pressures of opposing chambers are applied to either side of a sensing diaphragm. The position of the diaphragm is thus a function of the pressure difference between the two chambers. The change in position of the diaphragm is sensed by capacitor plates installed therein. A "differential" capacitance then generates DC voltage output to the conditioning circuit (see Fig. 15). The computation circuitry computes the indicated airspeed (IAS) using the following relation:

$$IAS = 1479.09\,(0.0334\, q_c + 1)^{2/7} \qquad (3a)$$

$$q_c = 1/2 \rho V^2$$

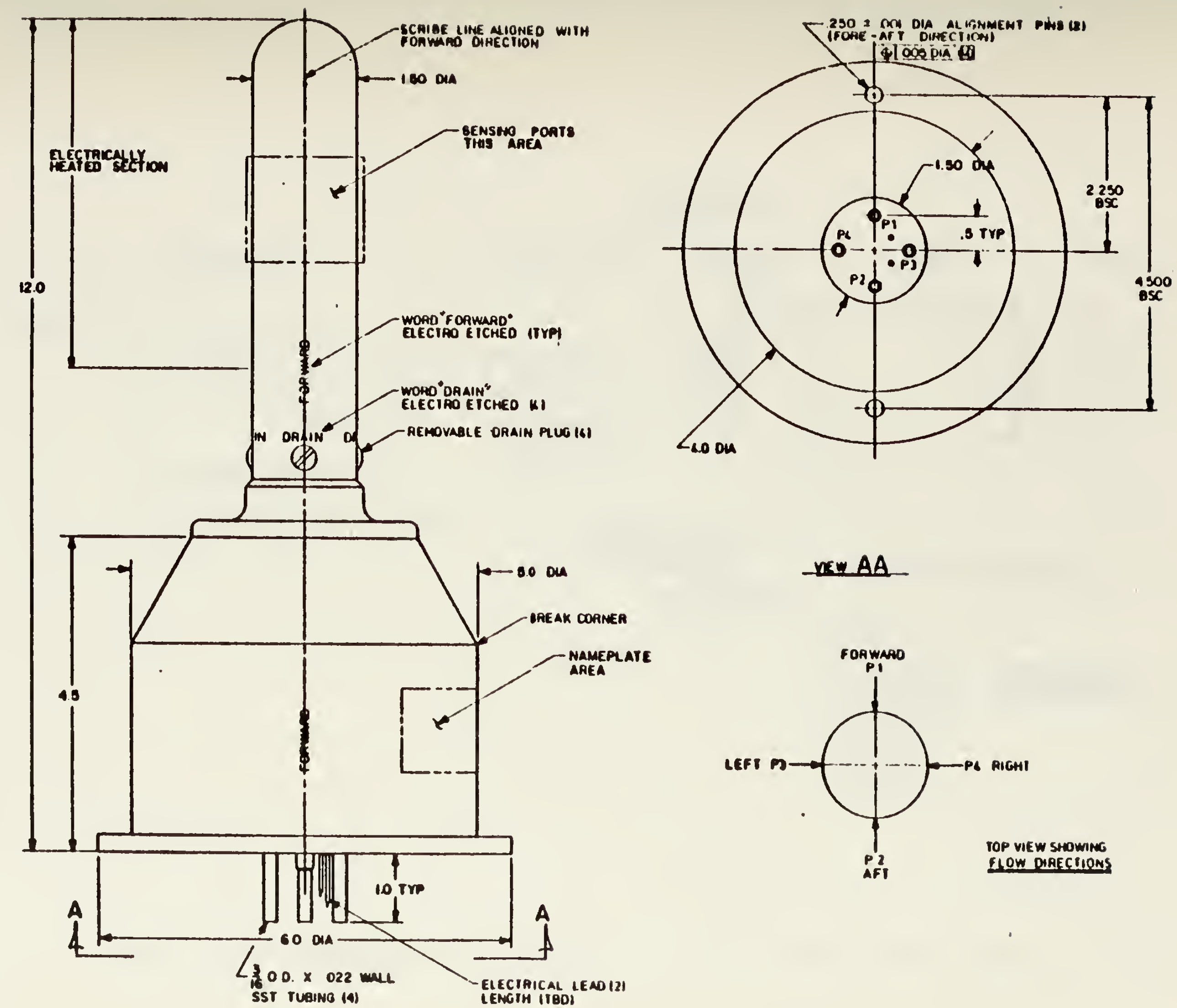


Fig. 13a Rosemount Sensor, Side and Top View

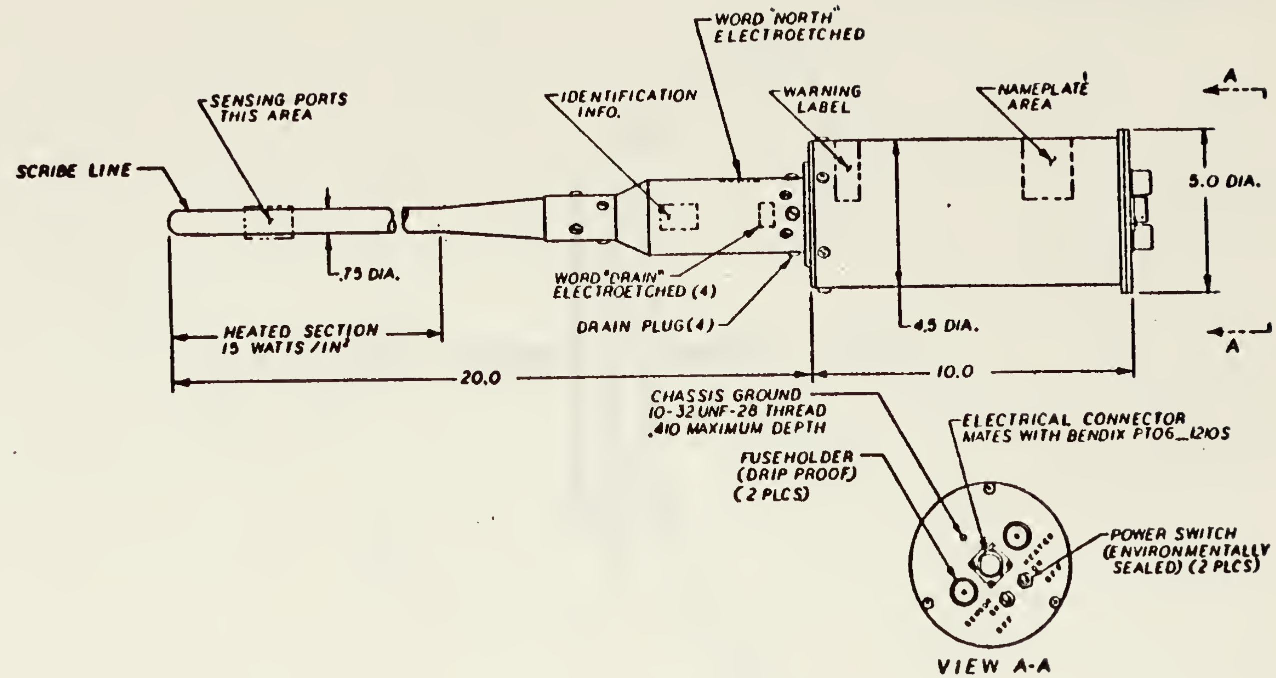


Fig. 13b Additional Details of the Rosemount Sensor

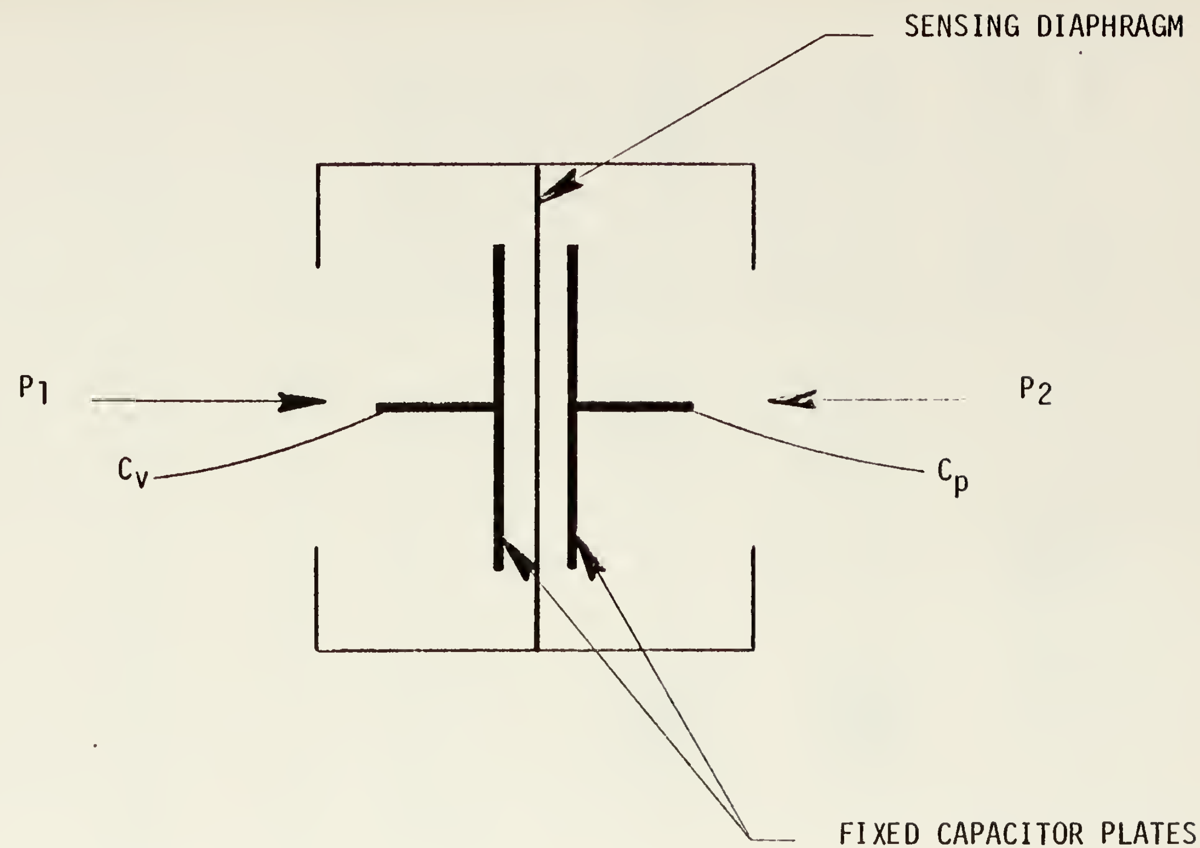


Fig. 14 Differential Pressure Sensor [3-4]

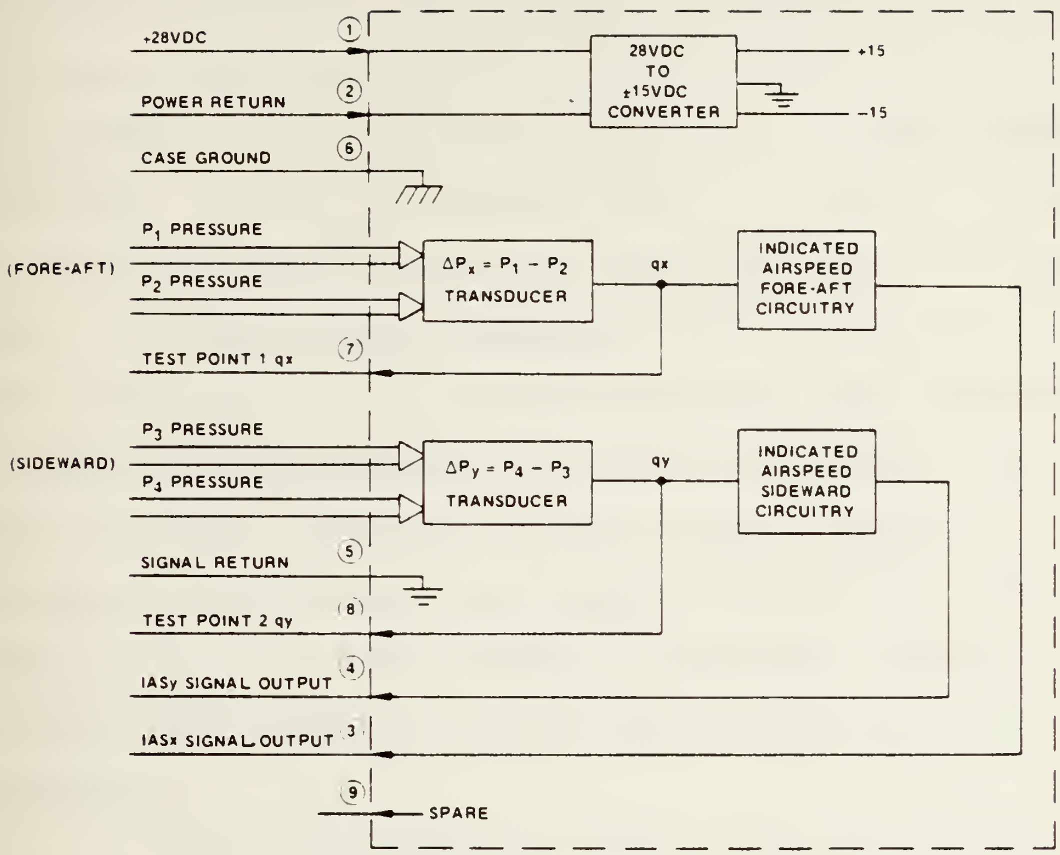


Fig. 15 Electronic Circuit for the Rosemount System [3-4]

d. Advantages and Disadvantages

The most obvious advantage of this system is its simplicity. Of all the systems examined, the Rosemount Orthogonal Low Airspeed system is by far the least complex. Although its mounting above the rotor results in relatively low accuracies (± 5 knots), there are no moving parts and the system is extremely light weight. The space above the rotor is in great demand for other uses. However, it appears that it is the best location for the sensor because of lack of rotor downwash and ground effect. A final notable advantage of the system is that the sensor and transducer are mounted together, thus eliminating many inherent disadvantages associated with piping. This provides a definite advantage over the "piped" systems, i.e., no time lag, no leaky joints, and simpler maintenance. The simplicity of the system becomes an attractive selling point for this sensor when considering ease of maintenance and replacement.

This system does, however, have its disadvantages. The sensor was designed to operate in the range of 0 to 50 knots. The sensing of the higher speeds requires the use of an additional sensor. Secondly, the system does not allow for simultaneous measurement of angle of attack (also a disadvantage of above-rotor mounting). A secondary system would be required for this measurement. Third, during longitudinal flight (sideslip) large random errors were produced (often as large as

±24 knots). This is totally unacceptable for nearly all operations.

e. Development Stage

The Rosemount system has been wind tunnel tested, flight tested, and is available on the market. Although not listed as an advantage, the availability should be considered as such since only three of seven newly developed sensors are available.

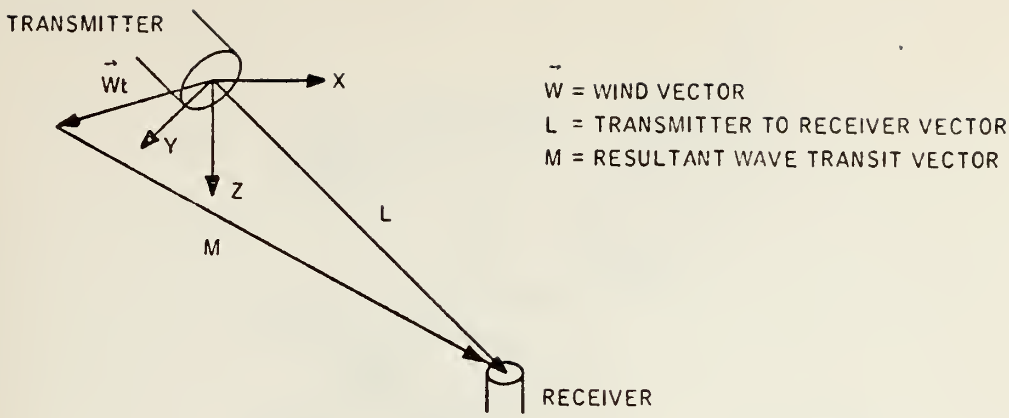
4. The Ultrasonic Wind Vector Sensor (UWVS)

a. Theory of Operation

This system has been developed by Honeywell, Inc., St. Louis Park, Minnesota [5]. Three orthogonal components of wind can be measured with this system. Fundamentally, for each component, there is an ultrasonic wave transmitted to an associated receiver. The relative wind flows across the transmission path of this wave and thus alters the transit vector of the wave in a manner that is proportional to the component wind velocity. Figure 16 illustrates one velocity component and the ensuing equations that must be solved. Figure 17 illustrates the full set of equations for all three components. The temperature must also be sensed to permit the calculation of wave velocity in the air.

b. System Description

Figure 18 shows the wind sensor configuration and the associated wind vectors (see also Fig. 19). The transmitters are located in the center of the sensor and are 75 kKz



$$\vec{M} = \vec{L} - \vec{W}t$$

$$\vec{W} = w_x\hat{i} + w_y\hat{j} + w_z\hat{k}$$

$$\vec{L} = \ell_x\hat{i} + \ell_y\hat{j} + \ell_z\hat{k}$$

$$|\vec{M}| = Ct$$

C = SPEED OF ULTRASONIC WAVE

$$(\ell_x - w_x t)^2 + (\ell_y - w_y t)^2 + (\ell_z - w_z t)^2 = C^2 t^2$$

Fig. 16 UWVS Vector Definition [5]

$$w_x = \frac{-R}{3}\left(\frac{1}{t_1} + \frac{1}{t_2} + \frac{1}{t_3}\right) + \frac{(c^2 - w^2)}{6R}\left(t_1 + t_2 + t_3\right)$$

$$w_y = \frac{R\sqrt{3}}{3}\left(\frac{1}{t_2} - \frac{1}{t_3}\right) - \frac{(c^2 - w^2)\sqrt{3}}{6R}\left(t_2 - t_3\right)$$

$$w_z = \frac{-R}{3}\left(\frac{2}{t_1} - \frac{1}{t_2} - \frac{1}{t_3}\right) + \frac{(c^2 - w^2)}{6R}\left(2t_1 - t_2 - t_3\right)$$

$$w^2 = w_x^2 + w_y^2 + w_z^2$$

$$c^2 = c_0^2\left(\frac{T + 273}{298}\right)$$

C_0 = 346.192 METERS PER SECOND

Fig. 17 UWVS Governing Equations [5]

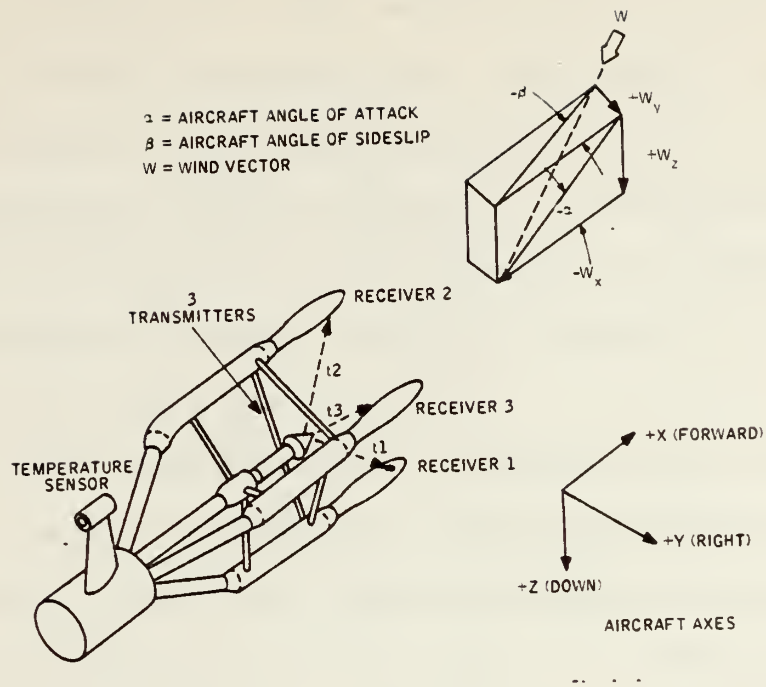


Fig. 18 Wind Vector Definition [5]

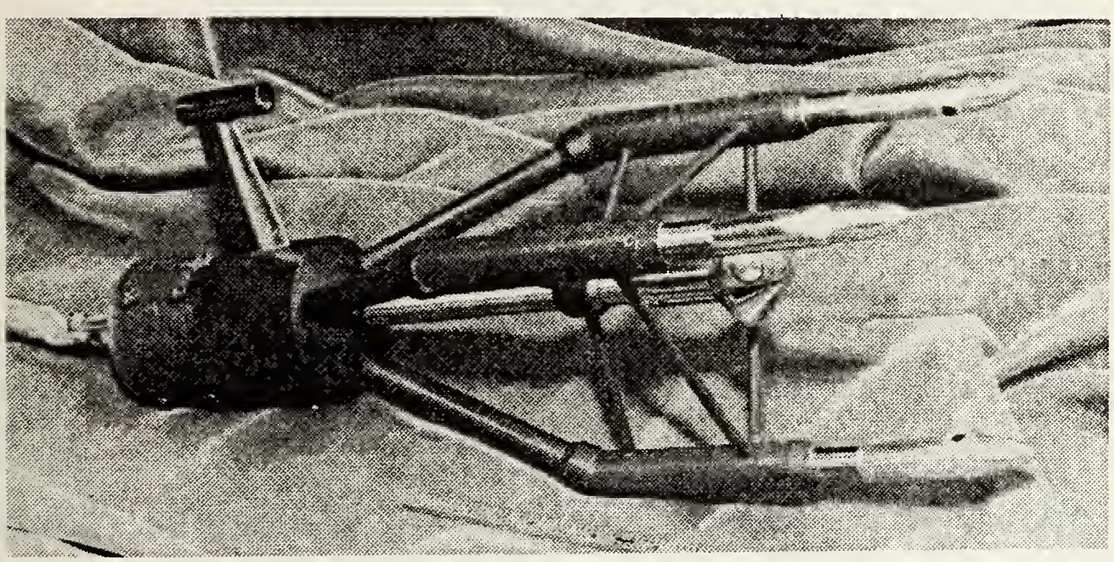


Fig. 19 Ultrasonic Wind Vector Sensor (UWVS) [5]

piezolectric transducers. The receivers are located one on each element around the tranmitters. The receivers are wide bandwith microphones with responses up to 400 kHz. The structure is lightweight tubular aluminum. The temperature sensor, mounted on the aft section of the sensor, is a platinum element thermally isolated from the rest of the sensor.

c. Associated Electronics

The system electronics consist of the receiver pre-amplifiers, temperature amplifier, and the computational electronics. The pre-amplifiers and the temperature amplifier are located in the afterbody of the sensor. The remaining electronics is in the aircraft. Figure 20 shows a block diagram of the system. Analog and digital units have been used to perform the computational functions.

d. Advantages and Disadvantages

The foremost advantage of this system appears to be the accuracy of measurement. The developer claims a linear measurement of velocity down to zero knots, accurate to ± 3 knots. There are presently no other sensors that can claim accuracies any better than ± 5 knots. Figures 21a, 21b, 21c, and Table 3 give a summary of the wind tunnel tests for velocities in the longitudinal, lateral, and vertical directions. Because of its linearity and accuracy, this system warrants further investigation. A second advantage of this system is that the sensor can be mounted either out on the nose of the aircraft or above the rotor. Figure 22 shows the mounting of

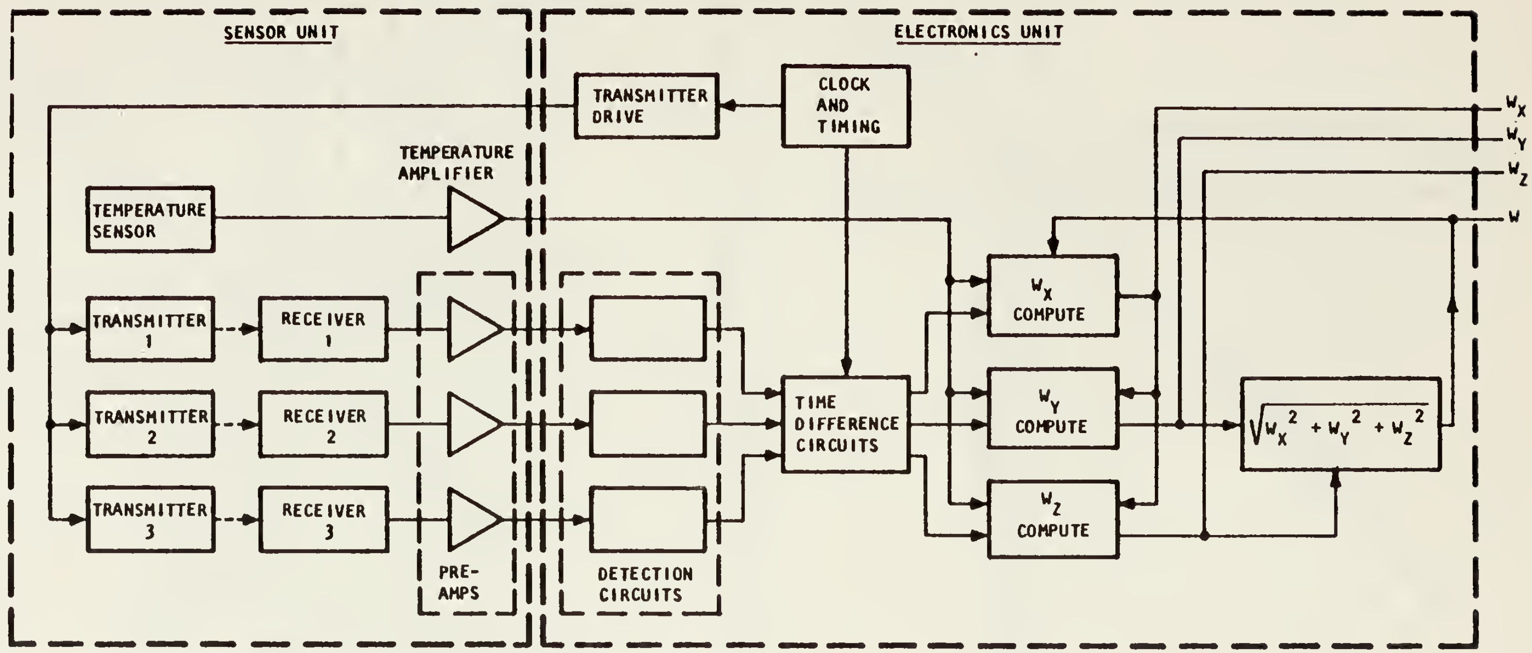


Fig. 20 UWVS Functional Block Diagram [5]

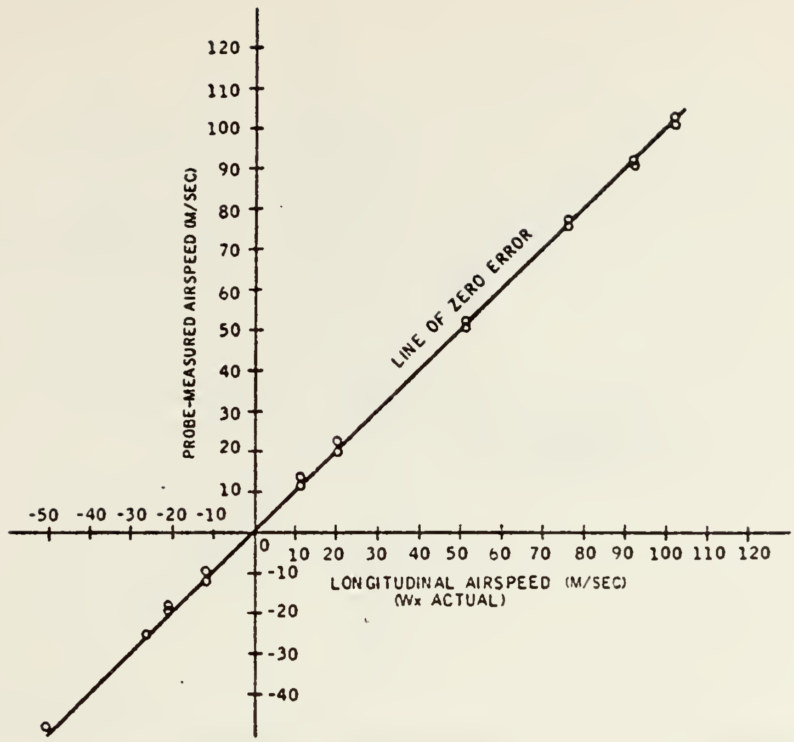


Fig. 21a Wind Tunnel Performance (Longitudinal Direction) [5]

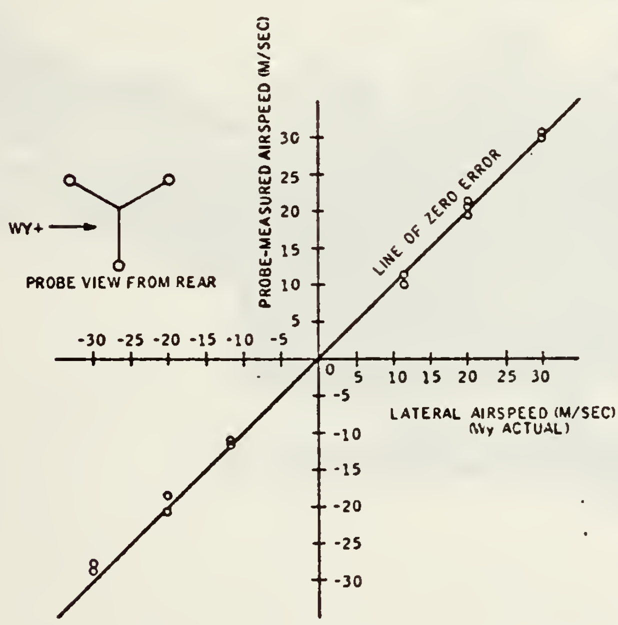


Figure 21b Wind Tunnel Performance (Lateral Direction)

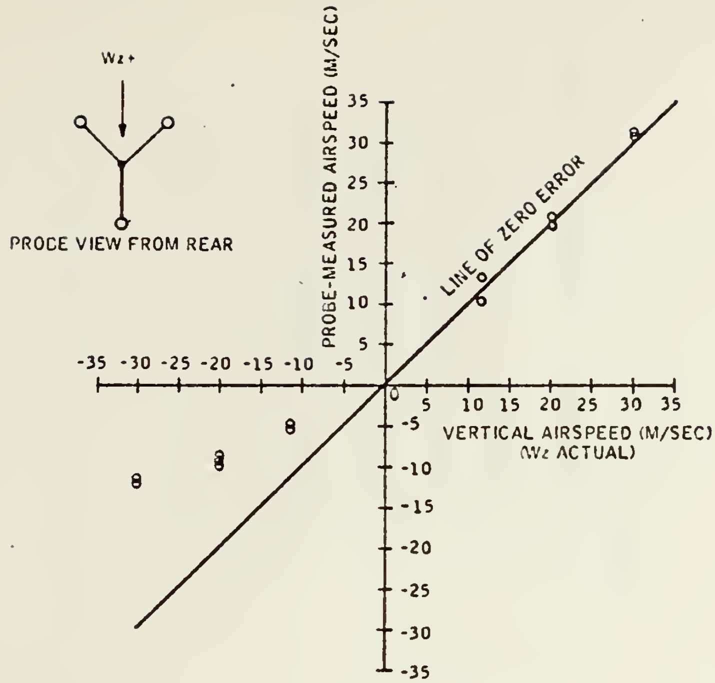


Figure 21c Wind Tunnel Performance (Vertical Direction)

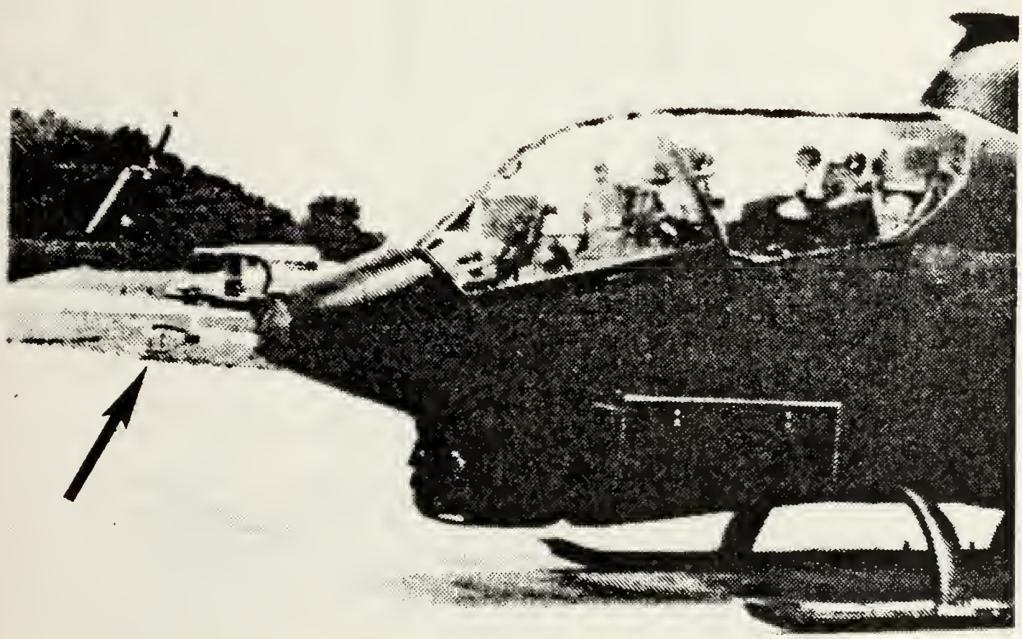


Fig. 22 Army Cobra Helicopter with UWVS Mounted on Nose Boom [5]

Table III

Wind Tunnel Test Results

Condition	Wind Velocity	Performance
$\alpha = 0$, $\beta = 0$	0-180 knots	W_x linear within 2 knots
$\alpha = 0$, $\beta = -30°$ to $+30°$	0-100 knots	W_y linear within 1 knot
$\beta = 0$, $\alpha = -20°$ to $+20°$	0-100 knots	W_z linear within 1 knot
$\beta = 0$, $\alpha = 0°$ to $-45°$	60 knots	W_x linear within 1 knot
$\beta = 0$, $\alpha = 0°$ to $-45°$	60 knots	W_z linear within 2 knots
$\beta = 0$, $\alpha = -90°$ (hover)	60 knots	W_x accurate within 1.4 knots
$\beta = 0$, $\alpha = -90°$ (hover)	60 knots	W_z accurate within 0.9 knot

the UWVS on the nose boom of an Army Cobra helicopter. In general, better results have been obtained from above-rotor mounting. A third and important advantage of this system is the lack of moving parts. This eliminates the possibility of moving parts corroding and freezing up. Finally, there are no pneumatics associated with the system. This factor in itself eliminates several problems: the time lag of the system is substantially decreased (this is accompanied by a corresponding increase in the frequency response); there are no pipe joints, thus removing the possibility of water leakage; the overall system weight is decreased; and the sensor mounting is made easier.

The list of the disadvantages of the system begins with the fact that the principle of operation UWVS is perhaps one of the most complex of all the systems explored. The possibility exists here of requiring specially trained personnel for maintenance, thus increasing the long term costs. Secondly, the associated electronics are substantially more sophisticated than those required by other systems. It might be added that with the projected data requirements, nearly all new systems will use extensive electronics. In any event, this results in an increase in the system weight that must be accounted for. Third, because of the sensor configuration, the velocities in the rearward direction cannot be measured with the same degree of accuracy as can the forward airspeeds. Additionally, mounting locations with the rotor downwash

produce more error than locations in the free stream.

e. Development Stage

The system has been wind-tunnel tested and flight tested on an Army Cobra helicopter with promising results. However, to date the system has not been placed on the market.

5. <u>Vortex Shedding Airspeed System</u>

a. Theory of Operation

This system has been developed by J-Tec Associates, Inc., Cedar Rapids, Iowa [6]. The sensor operation is based on the shedding of vortices from a bluff body. The air velocity across the sensor and the frequency of the shed vortices are proportional to each other, regardless of the air density or temperature (for Reynolds numbers larger than about 2000). Figure 23 shows the shedding of vortices behind a circular cylinder.

The vortex shedding frequency, the wind velocity, and the characteristic dimensions of the body are related by

$$f = SV/D \tag{4}$$

in which f represents the frequency of vortex shedding; V, the velocity of the wind; D, the characteristic dimension of the body (cylinder diameter); and S, the Strouhal number (essentially constant at S = 0.21).

Internal to the sensor, the vortex field passes through an ultrasonic beam. The vortex pairs tend to scatter the beam and reduce the energy impinging on the receiving transducer. This action effectively modulates the signal output from the sensor.

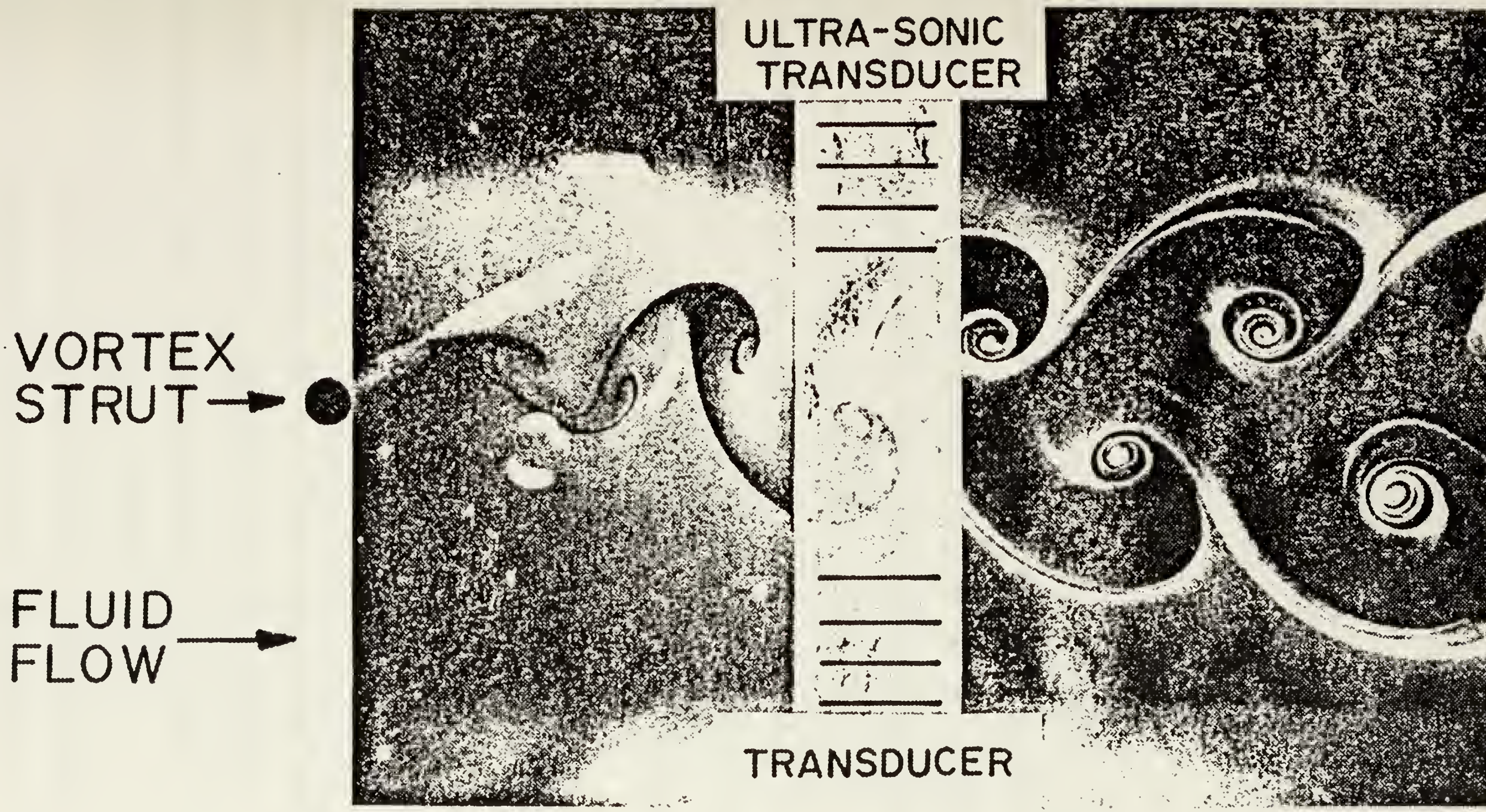


Fig. 23 Vortex Shedding Airspeed System [6]

The velocity components are measured by installing two or more sensors at fixed angles to one another. The velocity through each sensor is then the product of the relative air velocity and either the sine or cosine of the angle between the wind and the tube direction. A configuration for a two-tube sensor is shown in Fig. 24.

b. System Description

Figures 24-26 show the basic sensor construction. Figure 25 shows an early model primarily developed for fixed platforms. It was determined that the error produced with only two tubes 90 degrees from each other was unacceptable. Consequently, a sensor with three tubes, separated by 60-degrees was developed (see Fig. 26). In each tube there are two sets of sensing devices (vortex rod and associated transducers) so that the air velocity and direction may be determined.

c. Associated Electronics

Electronics in the form of a block diagram is shown in Fig. 27.

d. Advantages and Disadvantages

There are two fundamental advantages of this system. First, it lacks moving parts, thus requiring minimum maintenance. Secondly, there is no pneumatic piping required. The same reasoning applies here as was previously mentioned in connection with other systems (piping, leakage, etc.).

The first disadvantage of this system is that it is sensitive to icing and the size and roughness of the vortex rod.

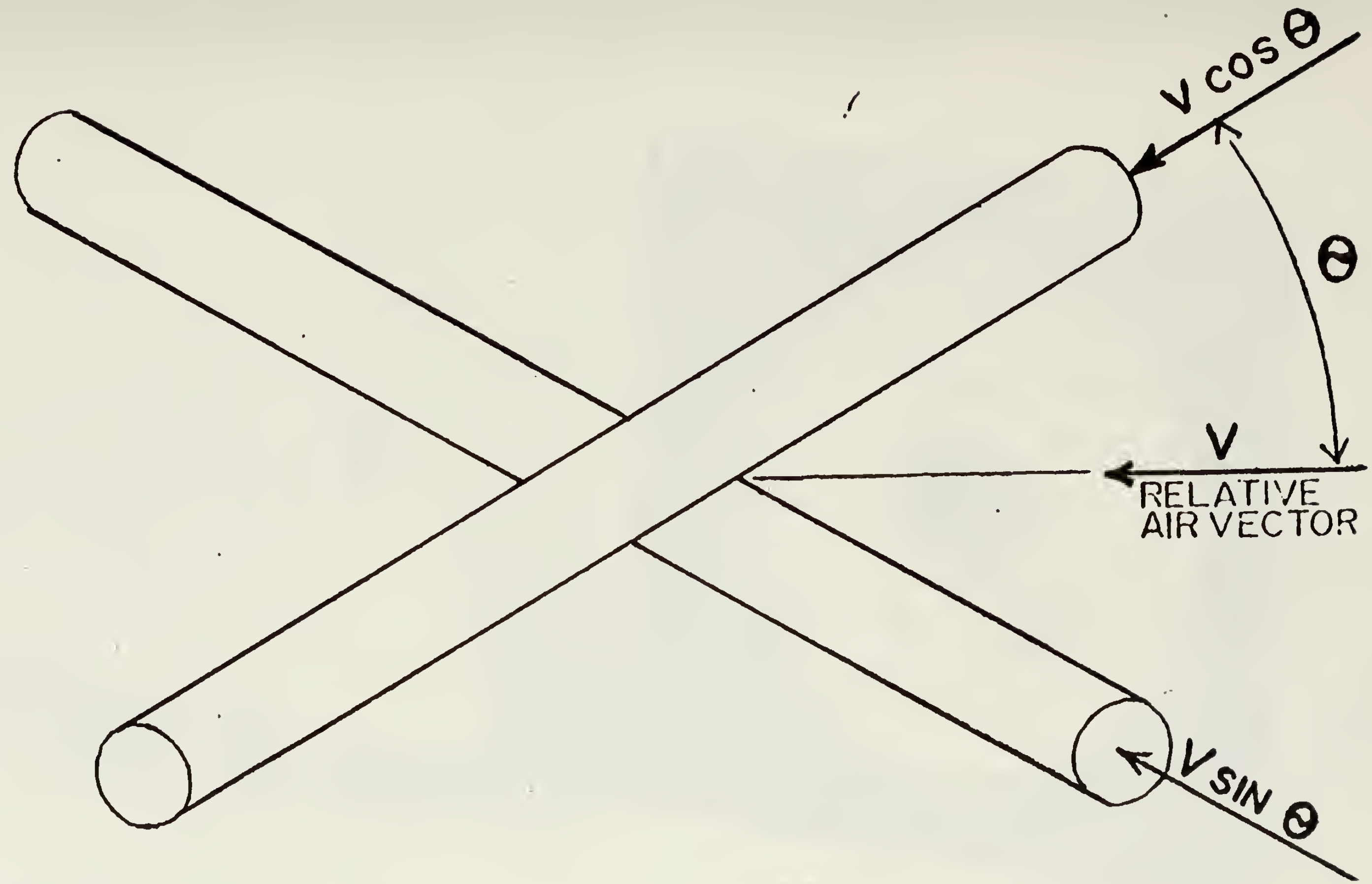


Fig. 24 Vector Tube Component Separation

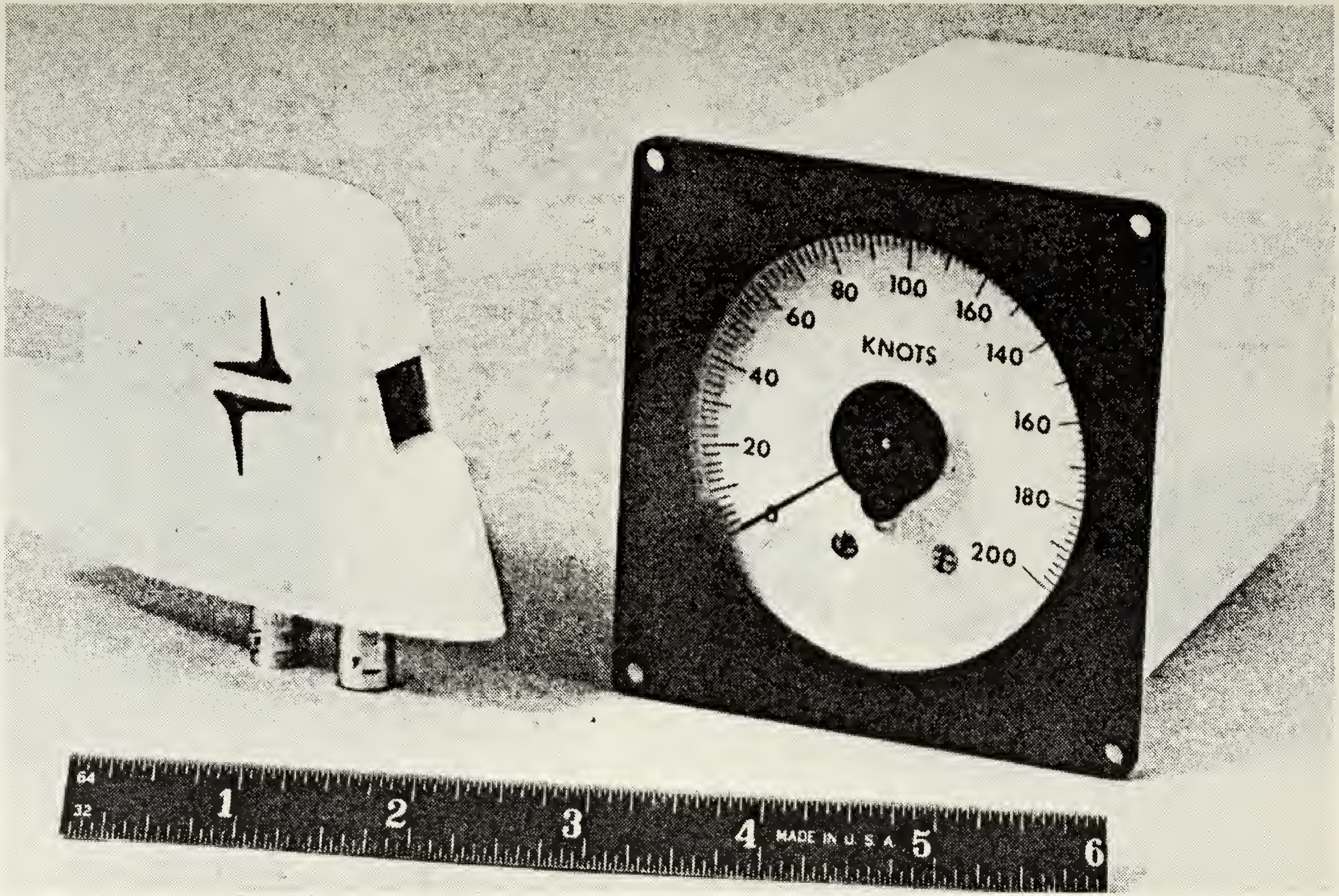


Fig. 25 General View of the Vortex Airspeed Sensor [6]

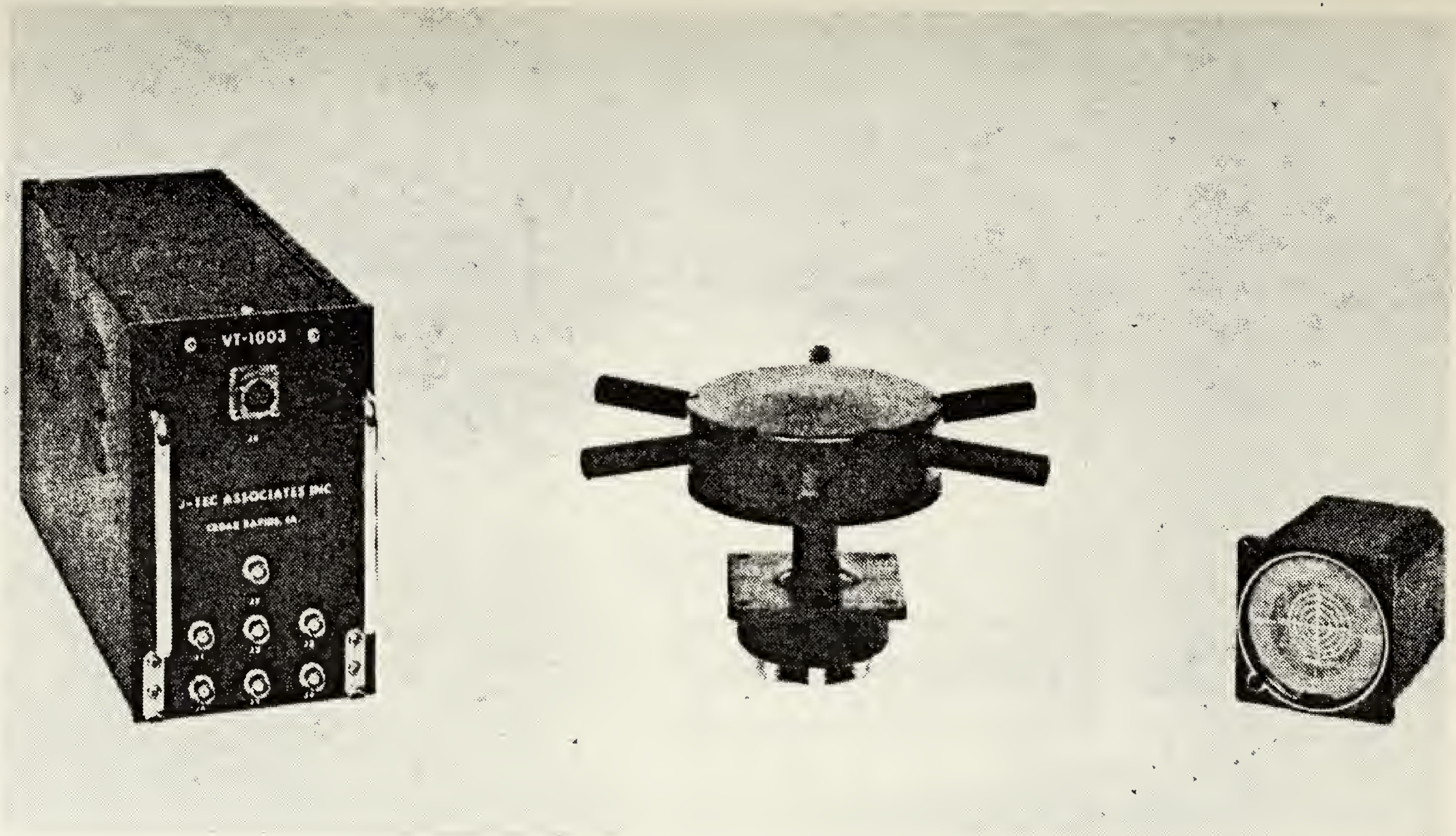


Fig. 26 Three Tube Vortex Airspeed and Direction Sensor [6]

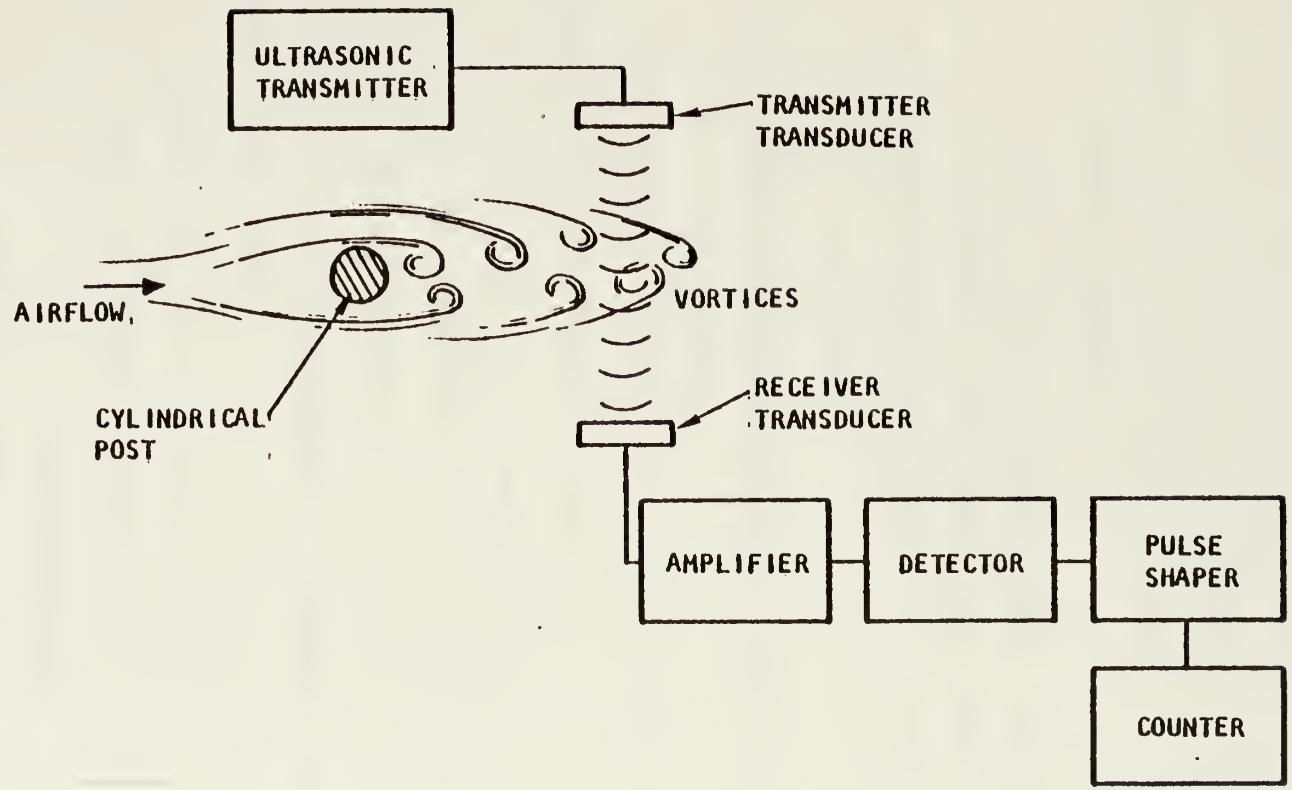


Fig. 27 Vortex Shedding Sensor -- Theory and Operation [6]

Secondly, while the electronics required is not substantially more than those of others, the concept of measurement makes this a fairly complicated system, requiring that maintenance be performed by other than standard maintenance personnel. Third, the accuracy of the system is extremely sensitive to the ground effect, angle of attack, and angle of sideslip.

e. Development Stage

Prototypes have been wind tunnel and flight tested. However, further developments have come to a stand still. Consequently, this system is not available as a finished product for installation on an aircraft.

6. Omnidirectional Low Range Airspeed Sensor (LORAS)

a. Theory of Operation

This system has been developed by Pacer Systems, Inc., Arlington, Virginia (see Fig. 28) [7-9].

The two shrouds at the ends of the arms house a venturi tube. They are connected to the differential pressure transducer at the center by means of the hollow arms. The arms are then rotated at a constant speed to produce a total velocity at the venturis consisting of the constant rotational speed and a sinusoidal variation of the relative wind vector. The pressure transducer output is then resolved into longitudinal and lateral components that are in turn demodulated to remove the modulating frequency. (See Fig. 29)

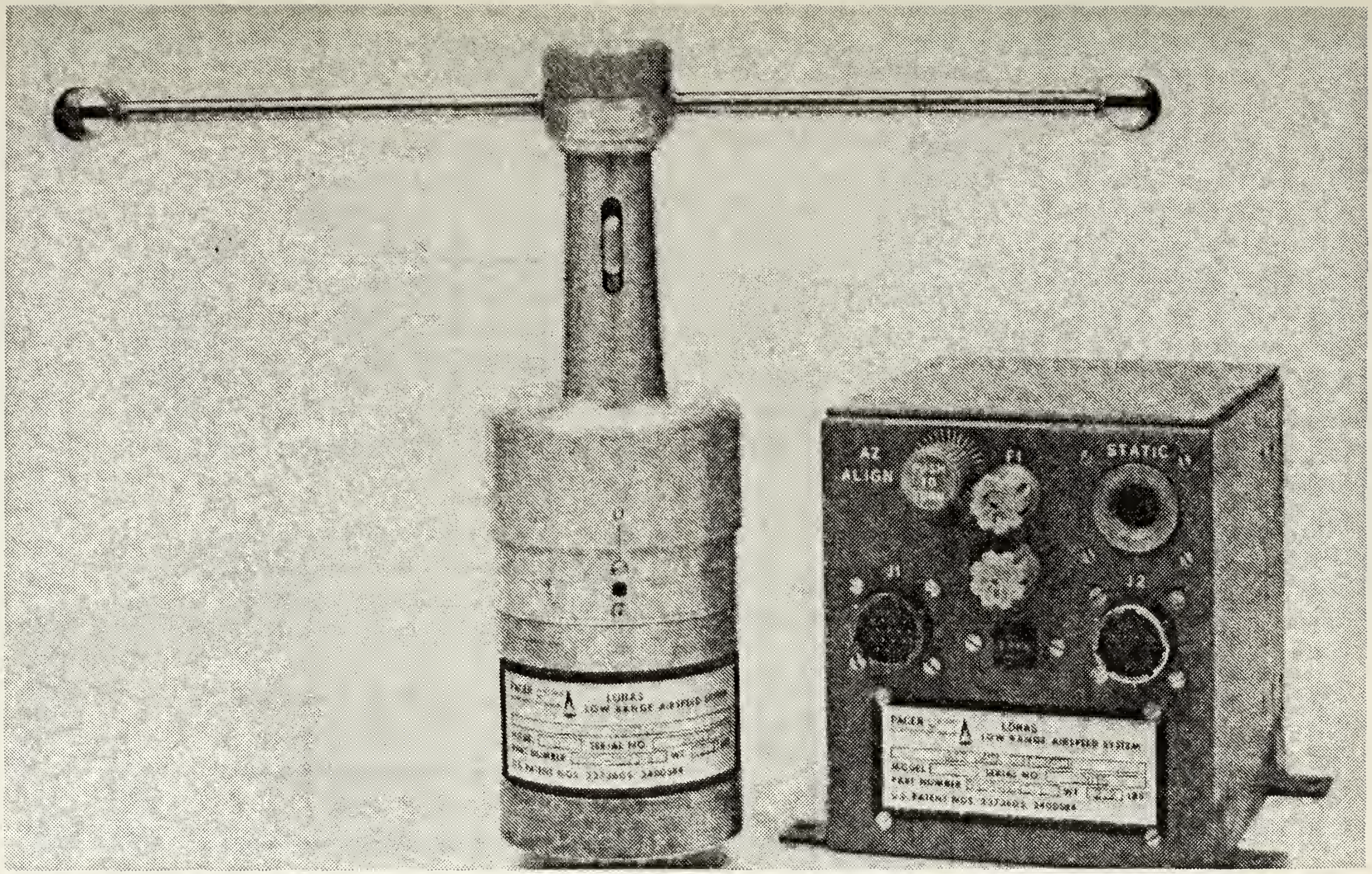


Fig. 28 LORAS (PACER) System Prototype for Pilot Production Configuration [7-9]

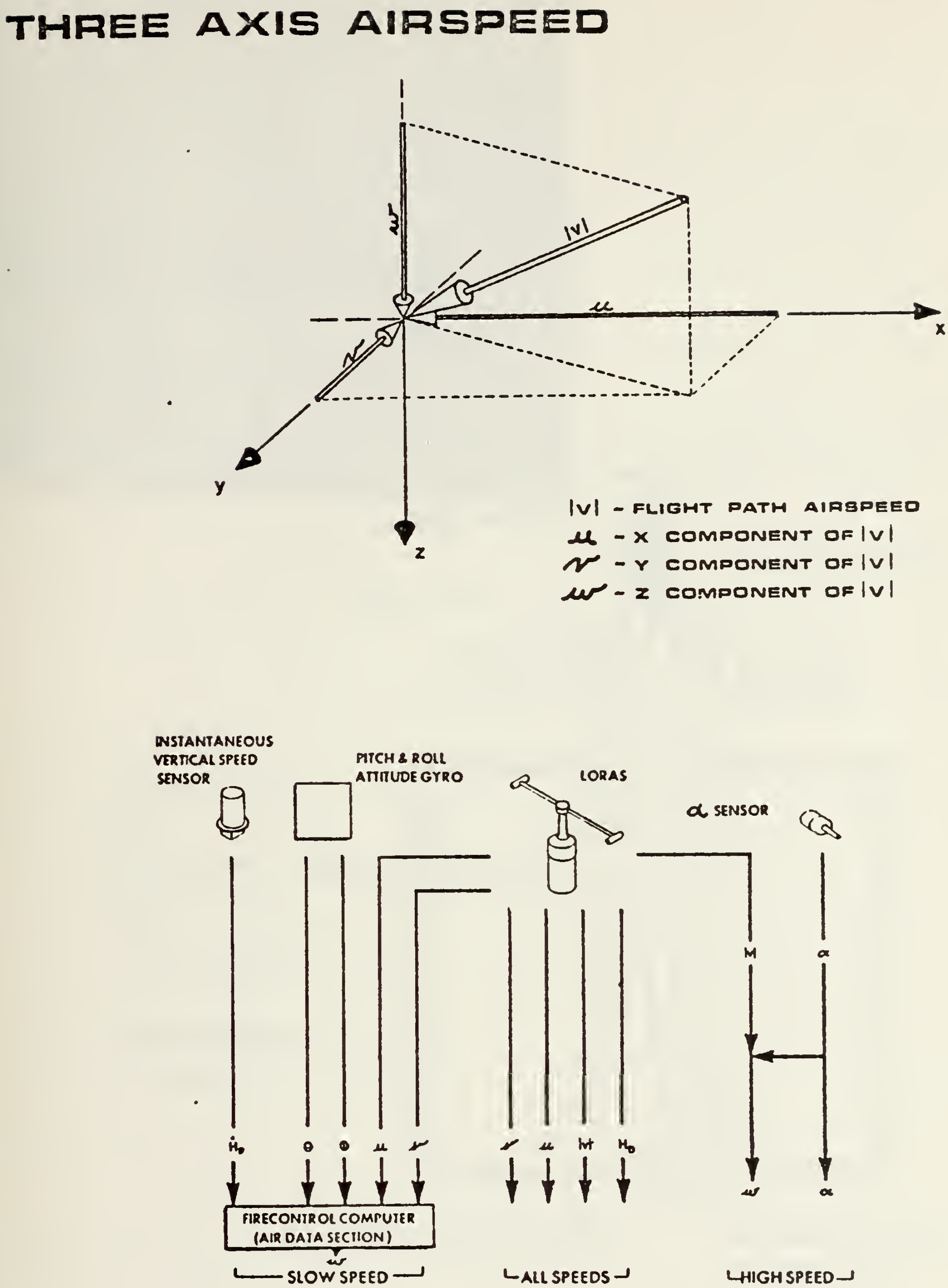


Fig. 29 Three Axis Fire Control Airdata [7-9]

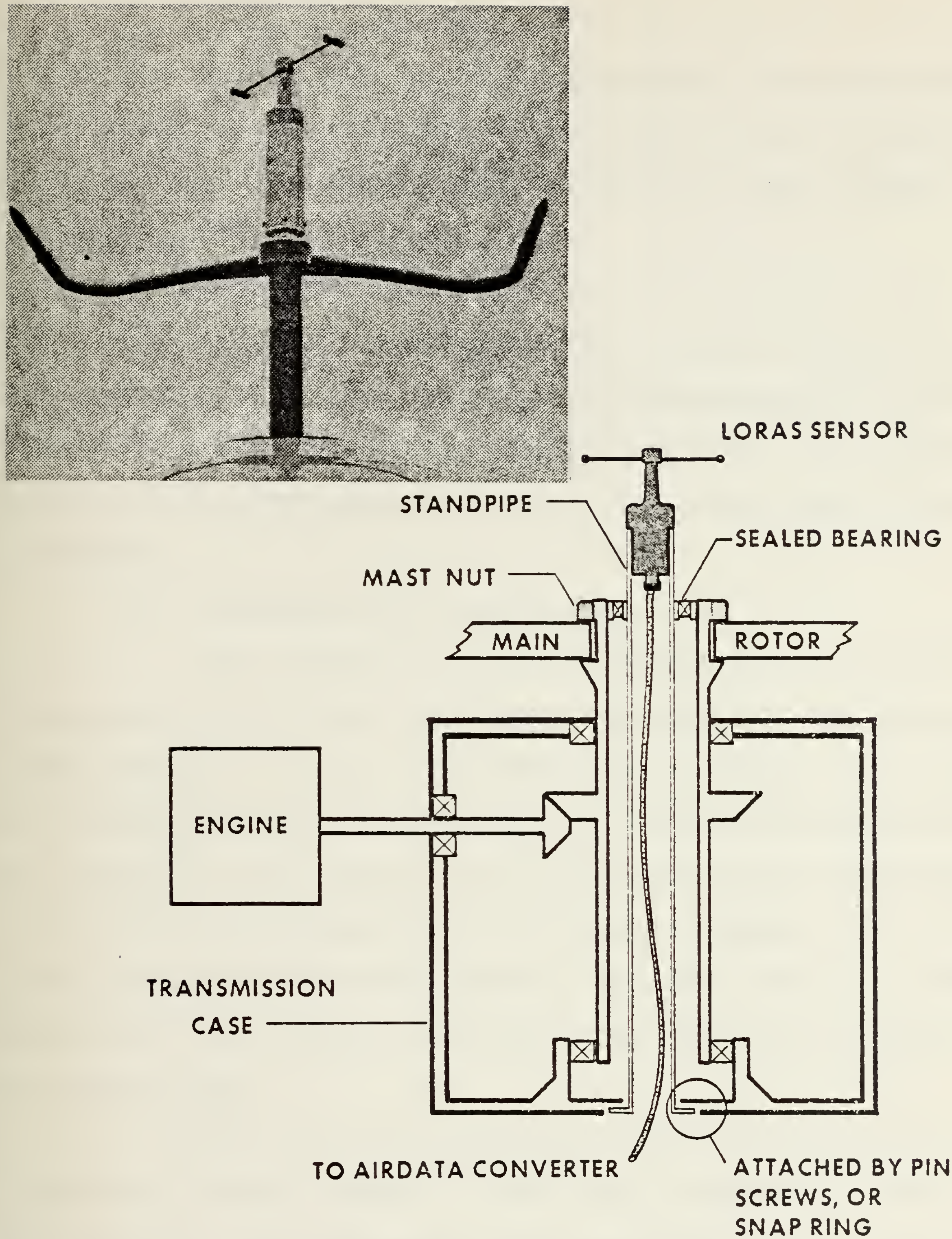


Fig. 30 Typical Standpipe Installation [7-9]

b. System Description

The venturi system is mounted on a constant speed motor which in turn is mounted atop a non-rotating standpipe (see Fig. 30). The sensor output is then led down through the standpipe to the air-data converter.

c. Associated Electronics

Although schematic diagrams were not available at the time of this writing, Pacer claims interchangeability between both digital and analog computing devices. Both systems would provide output to a fixed-face or a moving-face airspeed indicator.

d. Advantages and Disadvantages

This system is now on the market and is currently being tested by the Navy and Hughes Helicopters. The developer claims accuracies to ± 2 knots from zero to 200 knots and linearity within ± 3 knots. Considering the problems associated with the sensing of low airspeed, the two factors just cited make this system very attractive. Furthermore, although the rotating sensor cannot determine the vertical velocity, there is, integrated into the system, a vertical speed sensor and an angle of attack sensor.

When initially developed, the LORAS output was provided by an analog computer. Since then a compatible microprocessor has been developed, allowing either type of processor to be used in the system. This can be very advantageous in some situations.

As discussed previously, one requirement of a successful airspeed sensor is that it be able to measure wind speed prior to rotor engagement. LORAS can have airspeed measurements as soon as power is applied to the aircraft (this does not require rotor engagement).

There are many adverse environmental factors placed on airspeed sensors. Of the most serious effects are icing and collection of debris. The Pacer system reportedly handles these two problems quite well. Discussions with Pacer developers have revealed that both ice and debris are literally flung off the sensor by centrifugal force. For this reason Pacer claims that there is no need for a deicing system. However, due to customer demands a deicing system will be installed.

Finally, an advantage of this system, separate from the sensor, is the newly developed airspeed indicator. There are two basic types of indicators, a moving face indicator and a fixed face indicator, both of which provide for the pilot a 'picture' of his operating envelope.

Although LORAS is an impressive system, it is not without its disadvantages. First, it cannot, without a second sensor, measure the vertical speed. This inherently makes the entire system more complex. Second, the rotating nature of the device increases not only its complexity but also its maintenance time as well. Third, the system is in general much more expensive than any other system presently available. Finally, as the speed of sensor rotation slows, the gain of

the signal to the airspeed indicator must be increased. This requires that the air data converter sense the speed of rotation and generate an appropriate gain correction.

e. Development Stage

The LORAS is presently in its final stage of development. It is being evaluated by Hughes Helicopters for installation on board an Army unit. The system is also being tested by the Naval Air Test Center.

7. <u>Swivelling Probe Air Data System</u>

a. Theory of Operation

This system has been developed by Marconi Avionics, Atlanta, Georgia [10-11]. The system employs a Pitot static tube mounted to the aircraft in such a manner that it is allowed to move in two degrees of freedom relative to the aircraft. Figure 31 shows the sensor and its mount. The tail assembly is provided to keep the sensor aligned with the flow. The pressure signal is piped to the electronic processing unit which in turn provides output to the display.

There are no new flow sensing principles involved with this system. The basic sensor is still the Pitot tube where the change in pressure is proportional to the square of velocity.

b. System Description

Two angular resolvers are driven in the two axes of motion by the movement of the sensor head. The output of the resolvers is then fed to the electronic processing unit

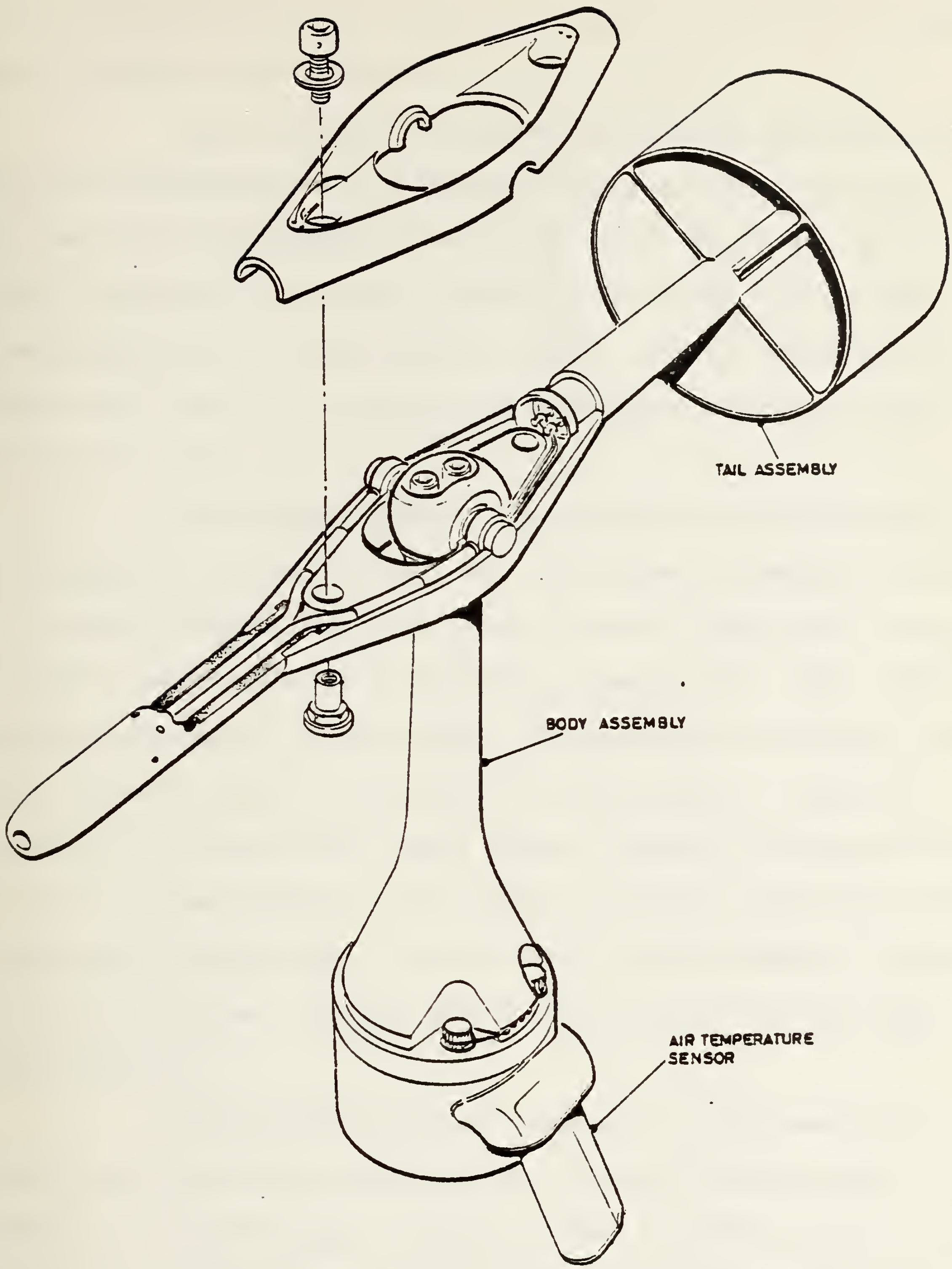


Fig. 31 Exploded View of the Swivelling Probe Airspeed Sensor [10-11]

where, together with the pressure signals, it is used to compute airspeed and direction.

This system is designed to utilize the rotor downwash and therefore must be mounted close up under the rotor. At speeds where the sensor is in the rotor downwash, the vector sum of horizontal airspeed and the rotor airflow is sensed. When operating at higher speeds (sensor not in downwash), the sensor acts much as a standard Pitot-static probe on conventional aircraft.

The sensing head of the sensor and tail assemblies are mounted as shown in Fig. 31. The dynamic pressure is piped to the body assembly via the piping system shown and a rolling flexible rubber tube at the gimbal arrangement. This method of transmitting the pressure was designed not to produce an error greater than 0.5 knots at the transducer. The static pressure is transmitted from a static chamber on the head to the body assembly which is at static pressure and then to the transducer. Drain holes are provided for the dynamic system. The static system is supposedly self-draining through other drain holes.

A deicing heater is provided in the head of the Pitot tube and can be provided for the tail assembly if required. The developer estimates that a heater for the tail will not be required because the preliminary estimates show that small amounts of ice build-up on the tail will not affect the sensor performance. At the base of the body assembly an

air temperature sensor has been mounted to provide a temperature input to the electronic processing unit.

Figure 32 illustrates the movement envelope of the sensor head.

c. Associated Electronics

The electronic processing unit (see Fig. 33) required in this system consists of four major parts: pressure-transducer unit which generates the pressure signal for input into the analog interface; analog-interface unit which carries the information received from the transducers, resolvers, and radar altimeter to the air data computer, and provides an analog output; air data computer unit which sotres error correction information to compare it with the output of the analog interface unit and provides required outputs to the automated stabilization equipment and the low speed indicator; and the power supply unit which provides power to all other electronic processing units.

In addition to those cited above, the electronic processing unit contains what is known as a BIT module. This module provides a self-test mode for the unit and a display portion for component failure in the system.

d. Advantages and Disadvantages

A principal advantage of the swivelling probe sensor is that it uses the rotor downwash in determining the airspeed, leaving the rotor-top free for other uses. However, it is questionable as to how effective this method is. The developer claims accuracies to ± 5 knots. The unit has been put on the

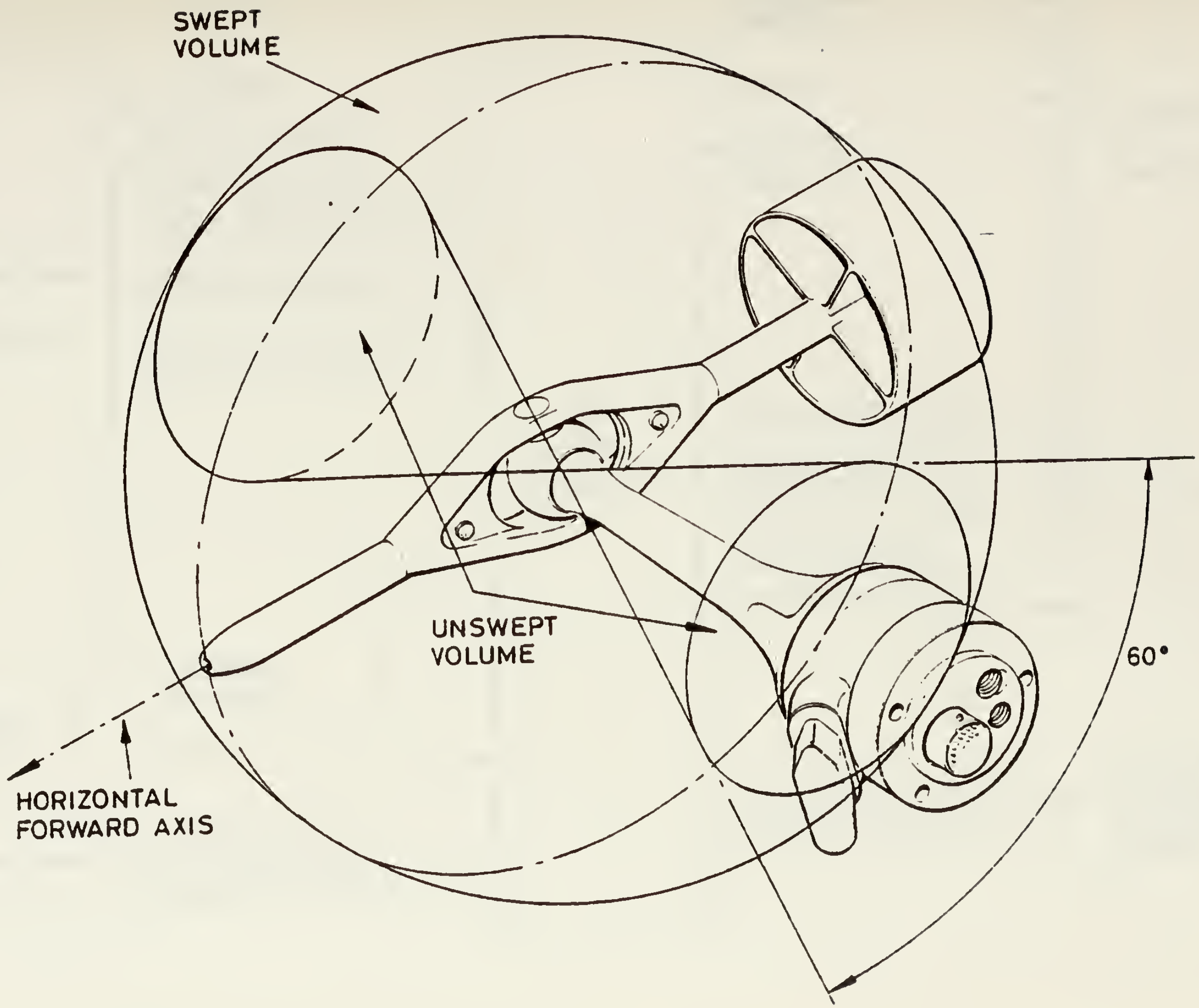


Fig. 32 Angular Freedom of the Swivelling Probe Airspeed Sensor [10-11]

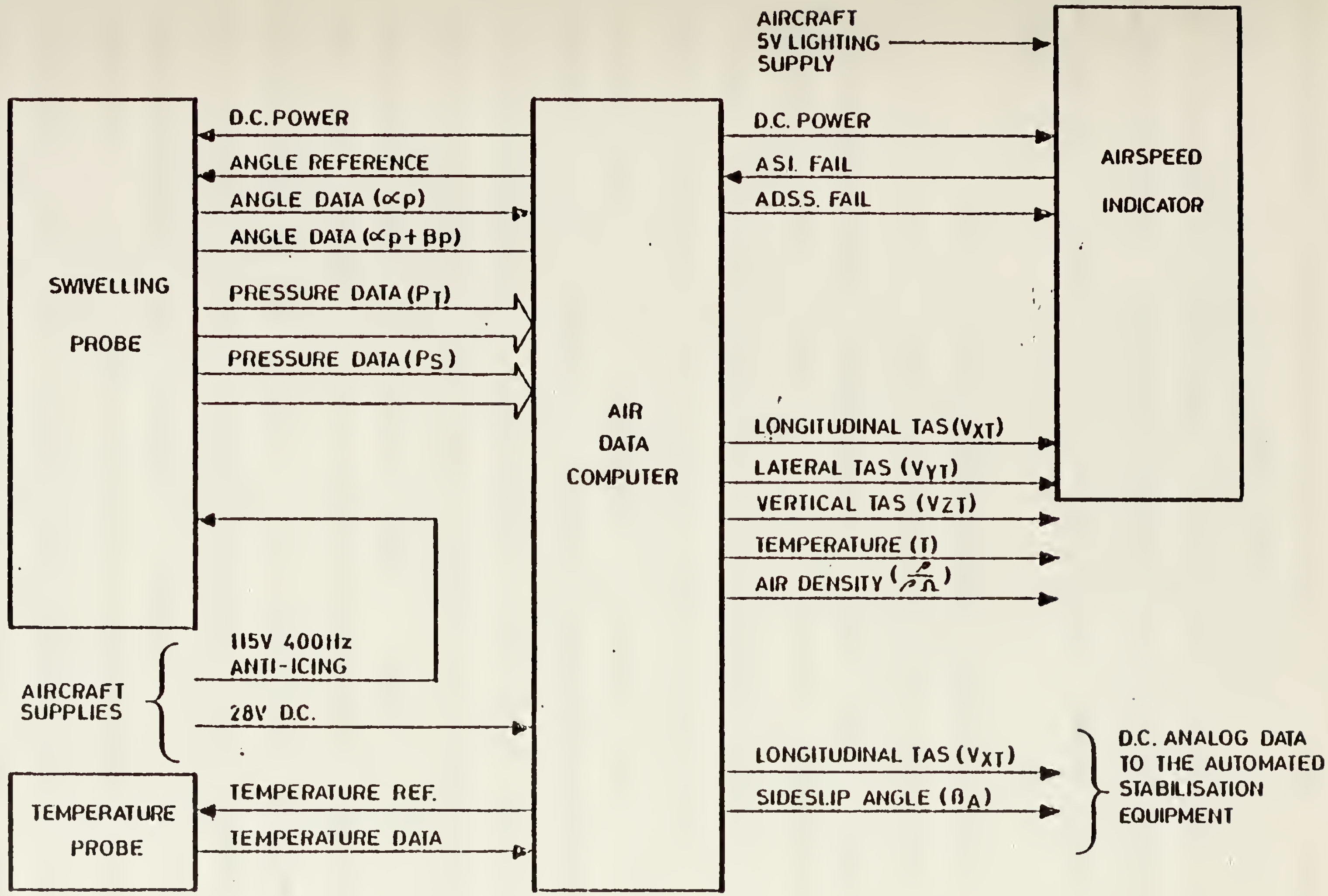


Fig. 33 Electronics for Swivelling Probe Airdata System [10-11]

market on the basis of about 21 years of testing. Secondly, the system will measure both the angle of attack and the vertical sink rate without additional sensors. Thirdly, what may be considered an advantage, is the newly developed low airspeed indicator (LAI). Both longitudinal and lateral components of the airspeed as well as the vector total can be read from this indicator.

The list of disadvantages begins with the fact that the sensor head is a moving part. Not only does this imply increased maintenance problems and a weak link for possible malfunctions, but it is the source of a serious degradation in accuracy. The transmission of the pressure signal through the gimbal introduces an error of as much as ± 0.5 knots. If the goal is less than ± 5 knots (preferably ± 1 knot) then ± 0.5 knots is indeed serious. Secondly, airspeed cannot be measured prior to rotor engagement. Consequently, the pilot does not know what the airspeed is in regard to his rotor-engagement envelope. This could result in serious damage. Thirdly, the developer claims that ice build-up on the tail assembly would not affect the operation of the sensor. It is difficult to agree with this statement since the sensor head and tail assembly should be in reasonably close balance. Consequently, the additional weight due to ice would definitely have an effect on the orientation and hence on the overall performance of the system. Fourth, when the system was in its initial test phases there was a great deal of effort to determine its ideal location on

the aircraft. It was noted that the location of the sensor was critical to the system accuracy. The question must therefore be asked "what will be the optimum location on an aircraft of different shape and geometry?" The possibility of a long test period to find the right location does seem to exist. Furthermore, modification on a given aircraft might deteriorate the performance of the system even if it were initially located at an ideal position.

Finally, a factor that must be considered by a potential customer, but not necessarily by the developer, is that the sensor requires a number of error corrections in order to linearize the output. These are: altitude rate, static pressure defect of the probe itself, region of flight, sideslip, lateral velocity, effect of weight changes (change of center of gravity), ground effect, effect of longitudinal airspeed, altitude rate, and pressure altitude (lateral airspeed cannot be measured with any degree of accuracy at airspeeds larger than 17 knots).

These error corrections not only make the electronics much more complex than other systems, but also preclude the possibility of using any air data converter other than the one specified by the developer.

e. Development Stage

Presently, Marconi is engaged in a contract with Bell Helicopters to supply air data sensors. Some tests are being carried out at Bell. Additionally, Marconi is developing

an integrated flight system for helicopters to include such parameters as engine torque, weight of aircraft, etc.

8. Fluidic Velocity Sensor

This sensor employs an axisymmetric free jet which must be exposed to the influence of the current [12]. In front and downstream of the emitter port one or two collectors recover some percent of the total pressure of the jet (See Fig. 34). The output of the sensor depends on the laminar or turbulent nature of the power jet. One can measure velocities as small as 0.25 ft/sec by properly adjusting the jet diameter, jet velocity, and the position of the receiver ports. For such velocities, however, the upper range of the sensor is quite limited.

The advantages of the sensor are that it is free from moving parts and it can be made to measure the total velocity and its direction. There are, however, numerous disadvantages as far as helicopters and V/STOL aircraft are concerned. First, the jets are unstable to environmental condiitons (thus unreliable). Secondly, the velocity range is limited. Several such sensors are required to measure horizontal and vertical velocities. Thirdly, the sensor requires extensive electronics to yield the velocities, angle of attack, sideslip, etc. Finally, the sensor has not been sufficiently developed to test in a wind tunnel let alone on an aircraft. Extensive additional work is needed to explore its potentials. It may be possible to develop a fluidic velocimeter through

the use of turbulent jets and multiple receiver ports which will enable one to measure lateral as well as vertical velocities.

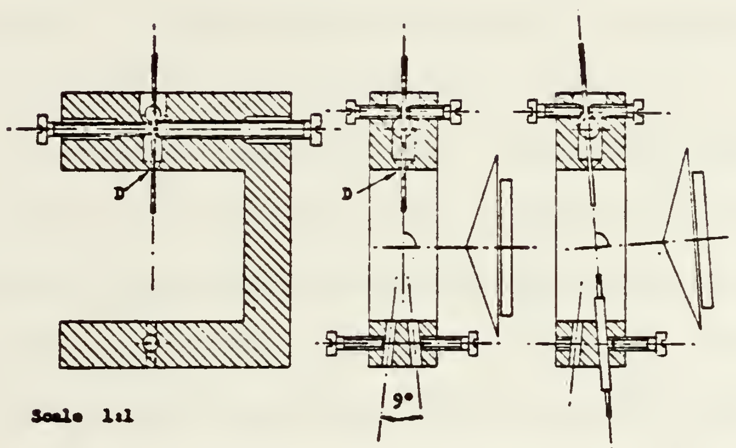


Fig. 34 Fluidic Velocity Sensor [22]

9. Axial Flow Turbine Airspeed Sensor

This sensor is developed by the Airometric Systems Corporation (AEROFLEX) as a true airspeed vector system.

The sensor is fundamentally an axial flow turbine mounted parallel to the flow. When the turbine speed is synchronized with the air flow its output is axial. When the turbine is not synchronized with the air flow its output contains an angular component (swirl component) which is sensed by an anemometer bridge that in turn causes a servo to re-synchronize the turbine. Thus, the system produces a turbine speed which is proportional to the airflow through the sensor.

The sensor is to be mounted on a swivel and positioned by a servo to follow the airflow. Tests indicate that accuracies of ±5 knots can be expected. However, the reliability of such a complex system with many moving parts is highly questionable. In addition, the mounting location will be critical in as much as the sensor configuration tends to alter the airflow around it. Further details of this sensor are not yet available.

D. CONCLUSIONS

In the foregoing, the characteristics of nine low speed air sensors have been examined in as much detail as possible. It has been demonstrated that a sensor system is comprised basically of two subsystems: one that interfaces with the air flow and one that converts the pressure or momentum signal to a usable output through electronics. The second susbystem may

further be broken down into the electronics and the electronic/ human interface (the display). Recently, there have been many improvements in the display portion of the air data system. Some of these have been described briefly, however, this work will not, in general, be concerned with the display portion of the system. The air-sensor interface may be fixed or movable. The complexity of the electronic circuitry depends on the type of the signal received and the method of data display.

It has been demonstrated that there is, at present, no sensor that satisfies completely the requirements discussed in Section I-B. In view of this fact, two important questions may be raised:

(1) Which, if any, of the existing sensors may be used immediately on a helicopter or V/STOL aircraft if no further research or development work were to be undertaken? It is understood that this action will be taken only to meet the immediate needs regardless of the shortcomings of the sensor, i.e., which sensor is the best among the existing ones?

(2) Should additional research work be undertaken to discover new ideas, methods, and concepts which will result in the development of low airspeed sensors which will meet the existing and anticipated needs of the helicopters and V/STOL aircraft?

After careful consideration of all the existing systems presented here and the requirements set forth, it became apparent that only three of the systems come close to being satis-

factory. Namely, the Omnidirectional Low Range Airspeed Sensor (LORAS) of Pacer Systems, the Low-Range Orthogonal Airspeed System of Rosemount, and Swivelling Probe Air Data System of Marconi Avionics. It also appears that the LORAS system is the one most advanced of these three and comes much closer to meeting the criteria set forth.

In regard to further research, it seems that the logical direction in which to proceed is to forsake the direct use of the Pitot concept. In other words, to remove the direct dependence of the airspeed measurement on the impact pressure of the oncoming stream (which is very low at airspeeds less than about 5 knots). The existing systems rely heavily on electronics to amplify the pressure signals received from the sensor. The initial differential pressure is limited in magnitude (in most of the sensors) primarily because of the fact that the signal is a consequence of a simple balance between pressure and velocity. The air-sensor interface does not amplify the signal prior to feeding it to the pressure transducer (as it would in the case of two interacting jets in a fluidic device). It appears that one can use new concepts to obtain a pressure signal which would employ momentum principles through the interaction of jets. Such a system will be comprised of no moving parts and will, hopefully, be able to measure all three components of the velocity.

One may also explore the use of laser devices. At present, very little work has been done in this area. The complexities

associated with the particle distribution in the atmosphere, laser-beam-particle interference, and the interference of many laser beams on board the ship may present serious difficulties.

II. JET INTERACTION SENSORS

A. INTRODUCTION

The need to develop a low-airspeed velocity sensor with no-moving parts and a relatively linear sensitivity throughout the operating range and without excessive electronic amplification of the signal led to the exploration of jet-interaction devices. In principle a power jet of constant velocity is deflected by a control jet of variable velocity (velocity of the aircraft) and the differential pressure on a probe, resulting from the deflection of the jet, is related to the ratio of the velocities of the control jet and power jet. Such a device will have many advantages over those studied previously if it can be demonstrated that there exists a suitable jet geometry for which the differential pressure is proportional to the said velocity ratio.

Ideally, an axisymmetric configuration will be required in order to sense the velocities in any direction. However, the inefficiency of the momentum interaction of two axisymmetric jets and possible nonlinearity of the differential pressure in terms of the ratio of the control and power jets led to the exploration of a two-dimensional device.

B. A TWO-DIMENSIONAL JET-INTERACTION VELOCITY SENSOR

1. Test Apparatus

The apparatus employed for the initial exploration of the concept was a modified fluidics amplifier (see Figs. 35a

and 35b). A cylindrical probe with a splitter plate was placed downstream along the axis of the power jet. It is a well-known fact that a turbulent power jet is comprised of an initial core and a fully-developed region as shown in Fig. 35a. The sensing probe must be placed in the fully-developed region. The length of the core region was calculated to be x = 1.29 inches using the relation

$$x_c = b/(\sqrt{\pi}C) \tag{5}$$

where b = 0.25 inches (the width of the power jet) and C = 1.09 (an experimentally determined constant [13]). The sensing probe was placed at x = 1.5 inches to allow sufficient distance for the development of the jet beyond the core.

Two pressure ports were provided at the midsection of the cylindrical probe (each was 1/32 inch in diameter). It has been previously shown [14] that the optimum position of the pressure ports is ± 45 degrees from the front stagnation point. The splitter plate prevented alternate vortex shedding and hence the periodic oscillations of the differential pressure at a frequency equal to the vortex shedding frequency.

2. Test Procedures and Results

The test system consisted of the jet-interaction device, flowrators, a differential pressure transducer, an electronic filter, and an amplifier-recorder system. The pressure transducer was calibrated using water and a simple manometer.

Experiments were carried out by varying the control velocity for a given power jet velocity. For each velocity

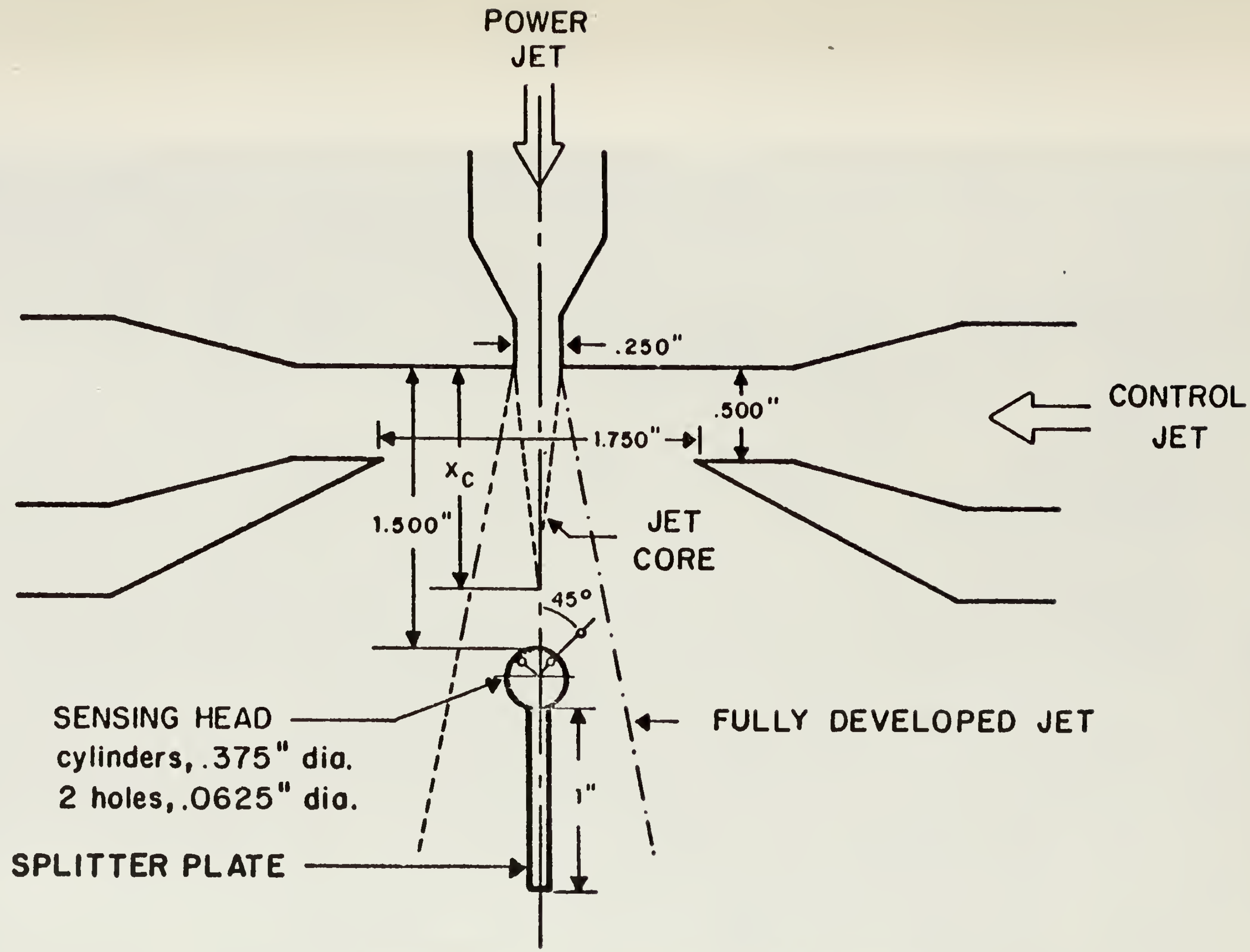


Fig. 35a Two Dimensional Airspeed Sensor Model

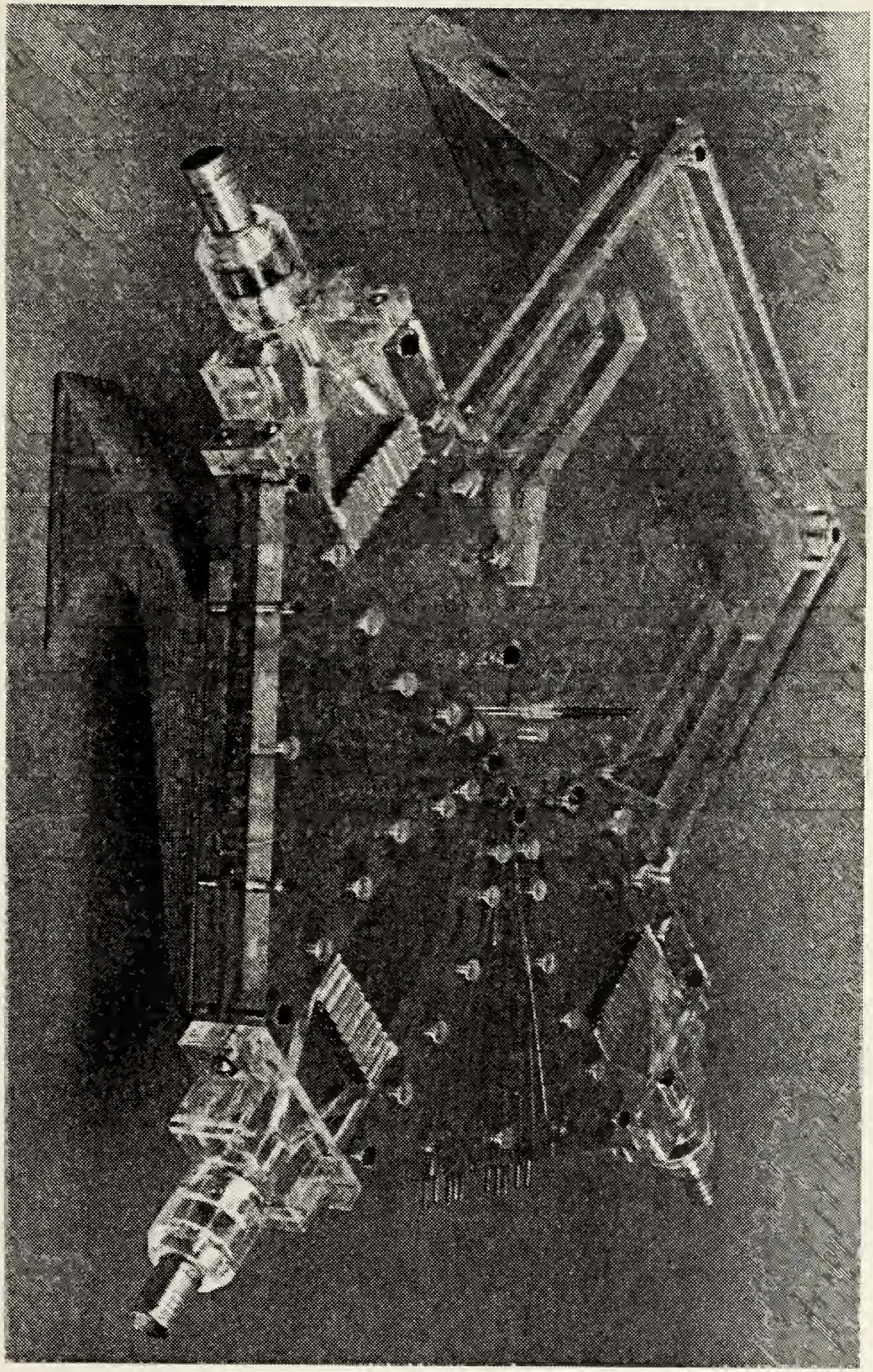


Fig. 35b Two Dimensional Airspeed Sensor Model

combination, the differential pressure was recorded on the strip chart recorder. Initially, experiments were carried out with relatively large power jet or nozzle velocities. However, in a subsequent series of experiments the nozzle velocity was considerably reduced in order to determine the lowest range of control velocities which could be sensed within the linear range of the device.

The results obtained with relatively large nozzle velocities are shown in Fig. 36 as function of V_c/V_n and the differential pressure, normalized with respect to the nozzle dynamic pressure. The results were found to be extremely encouraging. As seen from Fig. 36, the normalized differential pressure varied linearly with V_c/V_n less than 0.06 for all three power jet velocities.

The results of experiments conducted at lower nozzle velocities are shown in Fig. 37. The lowest control jet velocity was about 1 ft/sec. Once again a linear relationship was found between the velocity ratio and the normalized pressure. These results have clearly demonstrated the feasibility of the jet interaction principle for the measurement of low airspeed, at least for a two-dimensional system.

In order to further check the suitability of the data presented in Figs. 36 and 37, a straight line was drawn through the data (in the linear range) and the control jet velocities were calculated from this linear relationship. Figure 38 shows a comparison of the calculated control jet velocities with

those measured directly. It is clear that very low control jet velocities could be measured accurately within the linear range. As noted earlier, control jet velocities larger than about 20 ft/sec can easily be measured with a standard Pitot tube.

In concluding the discussion of two-dimensional jet-interaction velocity sensor, it is important to note that the errors associated with the flowrators, pressure-transducer calibration, strip-chart reading, and the geometry of the device amounted to an overall error of ± 4.5 percent. The error was somewhat smaller at larger control velocities.

The results obtained with the two-dimensional device were sufficiently encouraging for the design and development of an omnidirectional sensor based on the jet interaction principle and on a suitable combination of three two-dimensional sensors.

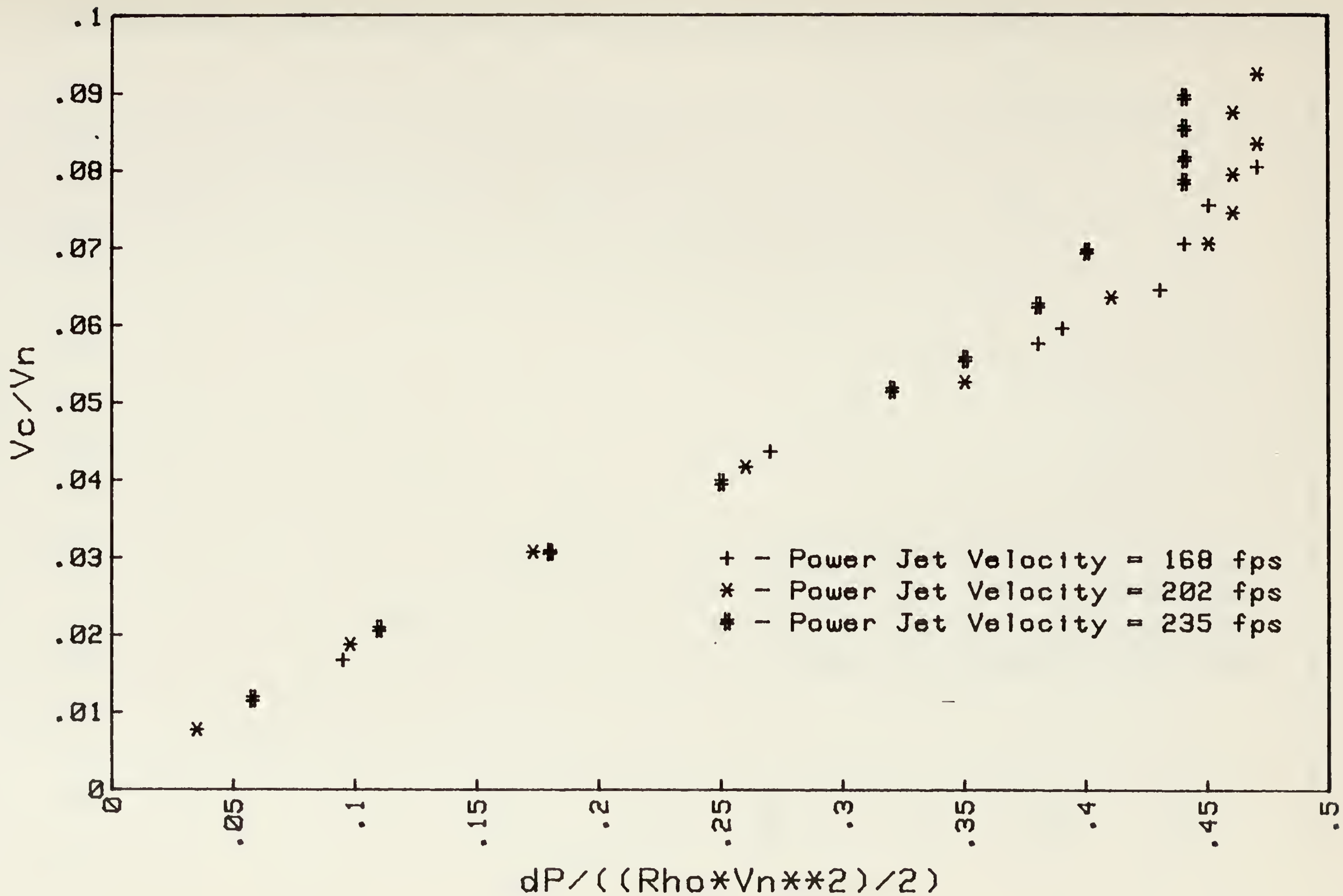


Fig. 36 Sensor Differential Pressure Versus Control Jet Velocity (High Range)

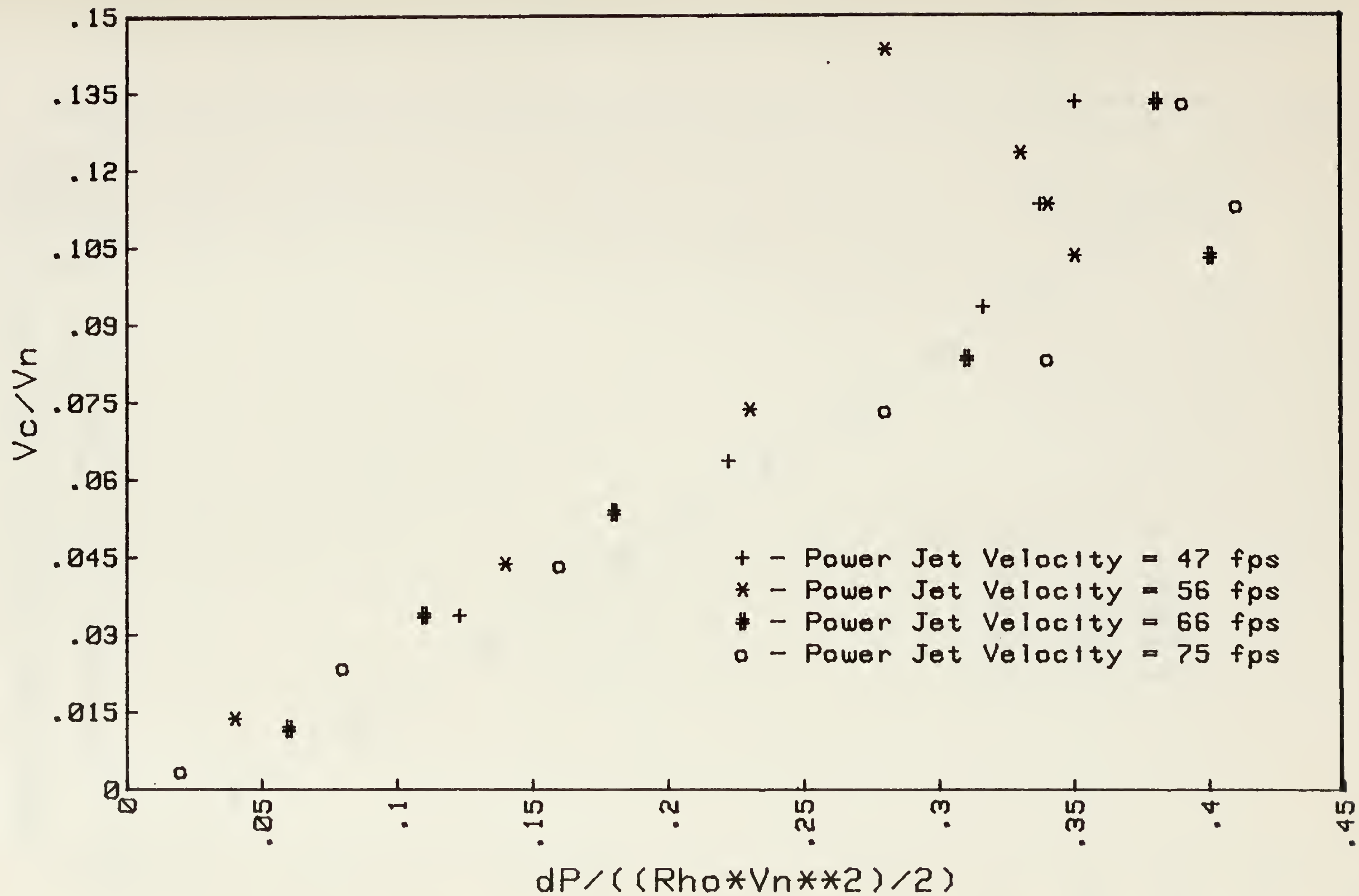


Fig. 37 Sensor Differential Pressure Versus Control Jet Velocity (Low Range)

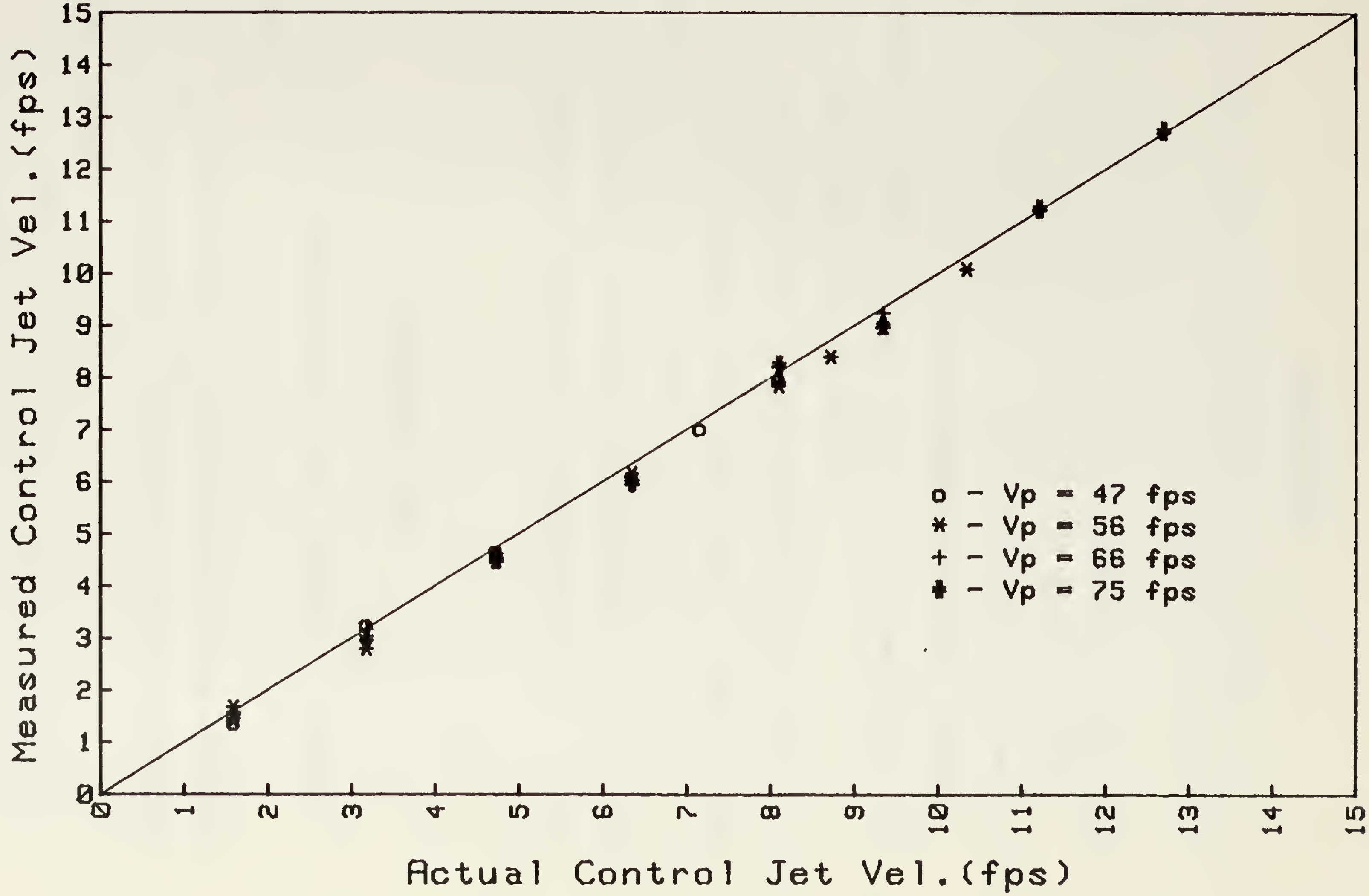


Fig. 38 Actual Control Jet Velocity Versus Measured Control Jet Velocity

III. CONCLUSIONS

The results of this investigation warranted the following conclusions:

1. Existing low airspeed velocity sensors are not quite adequate to sense velocities smaller than about 5 knots;

2. If no further research and development work were to be undertaken then the Omnidirectional Low Range Airspeed Sensor (LORAS) of Pacer Systems may be used immediately for velocities larger than about 5 knots;

3. The jet-interaction principle appears to yield a linear relationship between normalized velocity and differential pressure and may be used for velocities as low as 1 knot;

4. It appears that a suitable combination of three two-dimensional sensors can serve as an omnidirectional velocity sensor.

IV. RECOMMENDATIONS

The following recommendations may be made for further investigation:

1. The two-dimensional jet interaction device should be optimized so as to increase its pressure response and reduce its size and weight;

2. Suitable combinations of three such devices should be tested in various flow directions;

3. Suitable pressure transducers should be selected and the required electronic circuit should be designed;

4. The immunity or lack of immunity of the final configuration to environmental conditions (icing, dust, vibrations, etc.) should be explored; and finally,

5. The device should be tested on a helicopter and its performance should be compared with that of the existing devices.

LIST OF REFERENCES

1. Airesearch Manufacturing Co., "Study of Air Data Systems for V/STOL and VTOL Aircraft," Report No. 78-15047, January 1979.

2. Bolt, Beranek, and Newman, Inc., "The Optical Convolution Airspeed Indicator," Report No. AFFDL-TR-75125, Nov. 1975.

3. DeLeo, R. V., Hagen, F. W., and Jensen, D. P., "Low Range Orthogonal Airspeed System," Rosemount Report 5691, Rev C., 30 April 1976.

4. DeLeo, R. V. and Hagen, F. W., "Aerodynamic Calibration of Two Rosemount Model 874BF1 Orthogonal Windspeed Systems with 150 knots Full Scale Range," Rosemount Report 11784, Nov. 1978.

5. Proceedings of the 1976 Air Data Symposium, held at the Naval Postgraduate School, Monterey, CA., 22-24 June 1976.

6. J-Tec Associates, Inc., Internal report received from D. W. Beadle on 28 Feb., 1980, Marketing Manager, J-Tec Associates, Inc.

7. Proceedings of the 1978 Air Data Symposium, held at the United States Air Force Academy, Colorado Springs, Colorado, 2-5 May 1978.

8. Pacer Systems, Inc., "The Omnidirectional Airspeed Indicator Proposed for Operational Applications with LORAS, The Omni-Airspeed System," 1980.

9. Pacer Systems, Inc., General Information, Components, and Installation Brochure for LORAS, 1980.

10. Marconi-Elliott Avionic Systems Ltd., "Helicopter Airdata System," Pub. No. 260/691/5/L01, January 1978.

11. Marconi-Elliott Avionic Systems Ltd., "Collation of Flight Test Data Obtained from Swivelling Probe Air Data Systems," Pub. No. 260/687/5/R11, November 1977.

12. Pianta, P. G., "On a Fluidic Velocity Sensor for Very Low Velocities," Proceedings of the 5th Cranfield Fluidics Conference, Paper No. X5, 13-16 June, 1972, Uppsala, Sweden.

13. Kirshner, J. M. and Katz, S., "Design Theory of Fluidic Components," Academic Press, 1975.

14. Sarpkaya, T., "A Pneumatic Vortex Angular Rate Sensor-Analysis and Experiments," Automatica, Vol. 9, pp. 28-34, Pergammon Press, 1973.

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